24/7 renewable energy supply for electric mobility in the City of Paris

Executive summary of modelling tasks

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The project

The City of Paris as member of the C40 network strives to combat climate change, and since 2015 they have a 100% renewable electricity supply for their municipal demand. The procurement of guarantees of origin allows to certify that the same amount of electricity consumed is produced by renewable sources (wind, photovoltaic, hydro) on a yearly basis. However, this supply scheme does not consider a **real time matching** between demand and renewable production, which is variable and not necessarily available at all times. This means that the demand covered by guarantees of origin might not be supplied directly by the renewable production.

To address the limits of this approach, initiatives such as the *24/7 Carbon-Free Energy (CFE)* have been launched, with the objective of ensuring that every consumed kilowatt-hour is produced by carbon-free sources at **each hour of the year.** In this context, the programme *24/7 Carbon-Free Energy for Cities* launched by Google and C40 aims to encourage cities around the world to explore how to function entirely with carbon-free electricity at each hour of the year. This programme provides three pilot cities (**Paris,** London and Copenhagen) the technical assistance to assess the feasibility of a 24/7 carbon-free energy approach at an urban level.

C40 and the City of Paris engaged the consultants from Artelys and EY to realise the project "**24/7 RE supply for electric mobility in the City of Paris**" which aims to study the potential of matching **renewable generation** and **e-mobility** demand at each hour of the year, thus going beyond the current renewable supply contracts (guarantees of origin) that allow only matching on a yearly basis. The project is structured in three steps described below. This summary covers the **key results** from the first three steps, the fourth being tackled in a dedicated report.

1. Assessing the mobility charging demand within the whole City of Paris and the **RE Score from grid supply** for different **charging flexibility** scenarios, for 2030 and 2050
2. **Dimensioning the contractualization with (or investment on) capacities of RE and flexibility sources** in order to reach ambitious 24/7 RE scores
3. Analysing the **City-owned fleet demand** and RE scores from grid supply.
4. Develop an **action plan** for the implementation of the 24/7 RE strategy by the City of Paris.

What is the RE Score?

The **RE Score** indicates the share of the electric mobility demand that is covered by renewable energy (RE) on an hourly basis. The RE Score is computed for a whole year (8760 time steps).

These analyses have been carried out for the year 2022, using historical production data at European level, and for the years 2030 and 2050 using Artelys Crystal Super Grid simulations of the European electricity system. For 2050, two scenarios of the French electricity mix were considered based on prospective scenarios in RTE's Energy Futures study respectively. The **"Low RE" scenario** is based on the N2 scenario from RTE, which considers the development of new nuclear reactors in France from

2035 onwards, in complement of renewable integration. The **"High RE" scenario**, based on the M23 scenario of RTE, considers no new nuclear development in France, thus relying mostly in renewables for additional generation capacity.

The historical data and simulation results for each scenario were then used to calculate **RE factors** (the proportion of renewable generation in a kilowatt-hour consumed) for each hour of the year and RE scores.

1 Modelling of the city-wide electric mobility and grid-supply RE scores

1.1 A rapidly growing demand for charging dominated by passenger cars

The electricity demand from electric mobility[1] is expected to grow quickly, increasing close to 10 times by 2030 (453 GWh) with respect to 2022 (46 GWh) (see Figure 1). The main growth comes from the electrification of almost all passenger vehicles, in both residential and public charging points, as the City of Paris intends to end the circulation of combustion engines by 2030[2]. By 2050, the charging demand will remain stable, with several use cases seeing a reduction of demand due to a reduction of motorised mobility in the City of Paris and efficiency gains[3,4].

Overall, the **additional demand coming from the electrification of mobility** (450 GWh) **is comparatively low** to the City's total electricity demand (13 TWh in 2021). Therefore, by 2030 electric mobility would represent only 3,5% of additional demand in the City of Paris (if demand remains constant).

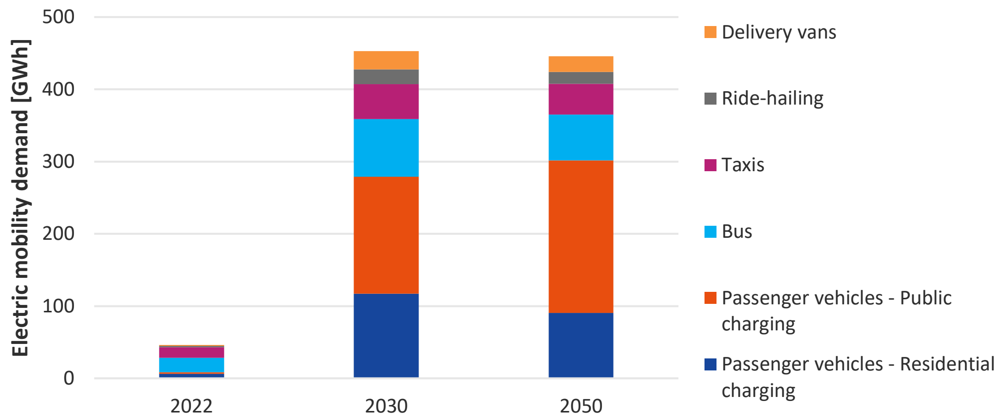

Figure 1 Charging demand in the City of Paris by 2022, 2030 and 2050

[1] Six use cases were considered: passenger vehicles in residential charging and public charging, taxis, ride-hailing, delivery vans and buses. Boats, metro, trains and hydrogen-based vehicles were not considered in this study.

[2] City of Paris, Paris Climate Action Plan

[3] The modelled demand scenario considered a reduction of car ownership by Paris' residents of 30% between 2022 and 2050, following current trends. Taxis, ride-hailing, buses, and delivery vehicles mobility demand was considered stable to remain stable.

[4] This scenario can be considered as a high charging demand by 2050. Policies seeking to reduce the use of motorized vehicles (in particular passenger vehicles) could reduce demand even further.

1.2 Charging flexibility allows high coupling with solar generation, but risks increasing peak demand

Three EV charging scenarios with varying degrees of flexibility were assessed:

- **Reference:** uncontrolled EV charging only
- **Flex:** smart charging for a share of the mobility needs
- **Flex+:** smart charging, V2G, and higher shares of daytime charging to allow coupling with PV generation.

It should be noted that in the Flex and Flex+ scenarios, **the charging was optimised to maximize the RE consumption (based on the RE factors) for each hour of the year.** The RE factors can vary for each day of the year, but are, in average, higher during midday due to PV generation in the French and European power mix[5].

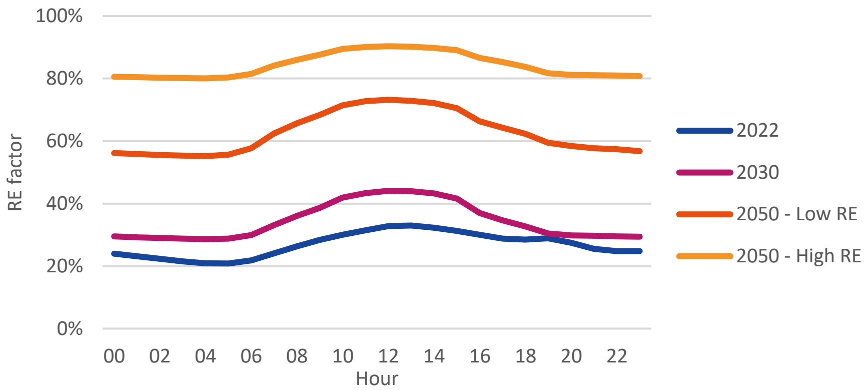

Figure 2 Average hourly RE factors in France

In Figure 3 and 4, the average charging profiles in the City of Paris for 2030 and 2050 respectively are shown. In the Reference scenario, two peaks are observed. First, a peak in the morning, related to public charging, and second an evening peak related to the arrival of Paris' residents to their homes and to buses to the garages. **Flexible charging allows to shift charging to the periods of the day with the highest RE share, which occurs mostly during the middle of the day**. The peak charging demand shifts from 9h-10h and 19h in the Reference scenario (uncontrolled charging), to the middle of the day in the flexible scenarios. By 2030, the peak demand coming from electric vehicle charging can pass from around 110 MW in the Reference scenario, to over 140 MW in the Flex+ scenario. The peak demand of electric mobility can be even higher by 2050, reaching over 300 MW (Flex+ scenario), as flexible charging becomes more widespread and the share of day-time charging increases.

[5] Exchanges between France and its neighbors were accounted for when computing the hourly RE shares. Prospective scenarios of the power mix see a large integration of solar PV, driving renewable shares up, as well as electricity prices down, during mid-day.

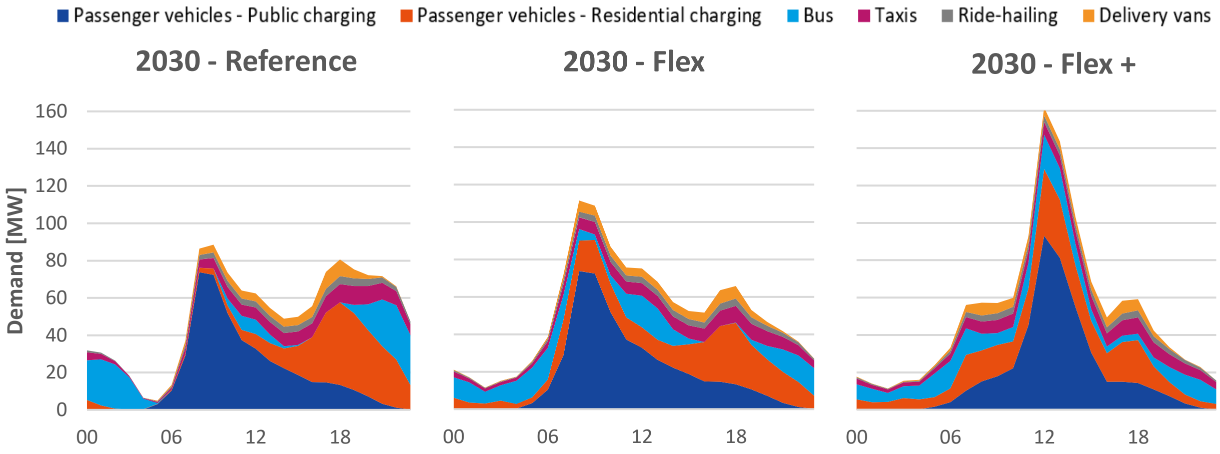

Figure 3 Hourly average charging profiles of the City of Paris for the three flexibility scenarios for 2030

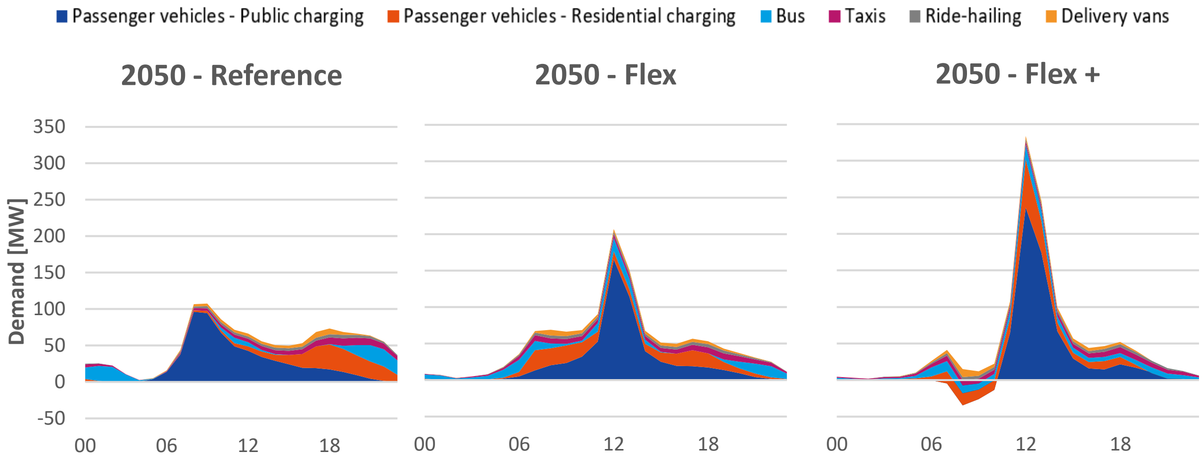

Figure 4 Hourly average charging profiles of the City of Paris for the three flexibility scenarios for 2050

The peak demand in Paris occurs between 10h-12h[6] during the coldest days of winter (historical peak demand in Paris is around 3500 MW in 2012). By 2030 electric mobility could increase peak demand at the City level by around 3% in the Reference scenario and up to 5% in the Flex+ scenario with respect to 2022's level. By 2050, the additional peak demand from EV charging could reach 10% of 2022's level, in the Flex+ scenario.

The increase in peak demand can potentially create congestions in the local distribution grid, requiring grid reinforcement investments (e.g., new power lines or transformers). A rough estimate of grid investments costs[7] shows that neglecting grid constraints can increase grid investment costs by around +2 M€/year, in the Flex scenario, and up to +6 M€/year in the Flex+ one with respect to the Reference scenario by 2030[8]. It should be noted, however, that these excessive impacts of the Flex and Flex+

[6] The peak demand period can vary depending on the neighborhood, with more residential areas seeing peak demand between 19h-21h.
[7] Based on recent grid investment values in the Ile the France region. A more accurate evaluation of grid investment needs would require to perform detailed grid simulations, which were out of scope of this work.
[8] Grid reinforcement costs were not computed for 2050 due to significant uncertainty on the evolution of demand and grid costs.

scenarios occur as the charging was optimized to maximize the RE consumption, and not to limit the impact on the grid (for example, by reducing peak demand).

These results show the importance of developing intelligent recharging strategies that take into account the physical reality of electricity networks**.** Experiments have already been carried out by distribution network operators, including Enedis (France's main DSO)[9], showing the feasibility of this approach. Moreover, flexibility to postpone grid reinforcements is already being procured by DSOs around the world, including Enedis[10], through auctions or flexible connection contracts.

It should also be noted that grid impacts should be assessed in a holistic fashion, considering the evolutions of other demand sectors, the integration of renewable generation in the local grid (rooftop PV), and the remaining margins of the power grid. The estimations carried out in this study can thus be considered as a worst-case scenario.

Thus, the he integration of electric mobility might not create additional constraints in the local grid, especially with the development of charging strategies that consider the grid operation, but also when considering the remaining margins of the local grid and possible synergies with other demand sectors.

1.3 Charging flexibility has limited impact on grid-only RE score

The RE scores of mobility closely follow the average RE share of the national electricity mix, as shown in Table 1. The flexibility of EV charging allows to increase the RE scores but only by a few percentage points (+2-5% depending on the level of flexibility and the electricity mix). This is mainly due to the limitation of the RE share of the grid[11], which does not allow a significant increase in the RE score. In addition, not all mobility is considered flexible (around 40% in 2030 and 60% in 2050 in the Flex+ scenario).

Grid-only supply does not allow the city to meet its targets, even with high levels of flexibility. Therefore, additional dedicated investment in renewables and flexibility would be required to further improve the RE scores.

[9] See for example the aVEnir project in France, or Electric Nation in the UK
[10] https://www.enedis.fr/co-construction-flexibilite-locale
[11] The French mix has a significant share of nuclear generation (not RE) at all hours of the year, limiting reaching really high RE shares even in during periods with high renewable generation.

Table 1 RE Scores of mobility for the assessed electricity mix and charging flexibility scenarios

Scenario	Average grid RE score	Mobility RE Score			City of Paris' objective
		Reference	Flex	Flex+	
2022	26.%	26.9%	-	-	-
2030	34.3%	35.5%	37.4%	39.5%	45%
2050 – Low RE	62.6%	64.9%	68.3%	70.2%	100%
2050 – High RE	84.2%	85.5%	87.6%	88.7%	

2 Dimensioning the renewable supply contracts to reach the City's targets

2.1 By contracting with dedicated renewable energy resources, the City of Paris' 2030 targets can be met with little additional cost.

The necessary renewable capacities that allow to reach different objectives of RE scores were identified using an ad-hoc optimisation model[12] and are shown in Figure 5, and the associated supply cost are shown in Figure 6.

Achieving the city's 2030 target of 45% of 24/7 RE generation will require contracting with 30 to 40 MW of wind[13], with small additional costs compared to grid-only supply (between +400 to +700 k€/year, +2% to +3%). It is possible to achieve even higher 24/7 RE Score targets by contracting with additional RES capacity, with increasing but manageable additional costs.

Charging flexibility can provide significant benefits, by reducing the amount of renewable capacity required to meet a given renewable energy target and reducing the cost of supply. The economic benefits of implementing flexibility can offset the additional costs of contracting for renewable energy. For example, it can be cheaper to achieve a 60% RE score with flexible charging (Flex scenario) than with grid-only supply without flexible charging (Reference Scenario, with a 35% RE score).

It should be noted that the economic benefits of charging flexibility (around 2M€ for the Flex scenario, and between 3-4 M€ for the Flex+ for supply costs) can only be maintained if smart charging strategies that account for grid constraints is developed, to limit the impact of EV charging on the grid (see Section 1.2).

[12] The model co-optimised the capacities of renewable generation (wind, PV) and flexibility (batteries), with the flexible operation of EV charging.
[13] This amount of renewable generates between 63 and 85 GWh, covering only 14%-19% of the mobility demand in a yearly basis. The rest of renewable supply comes from the grid.

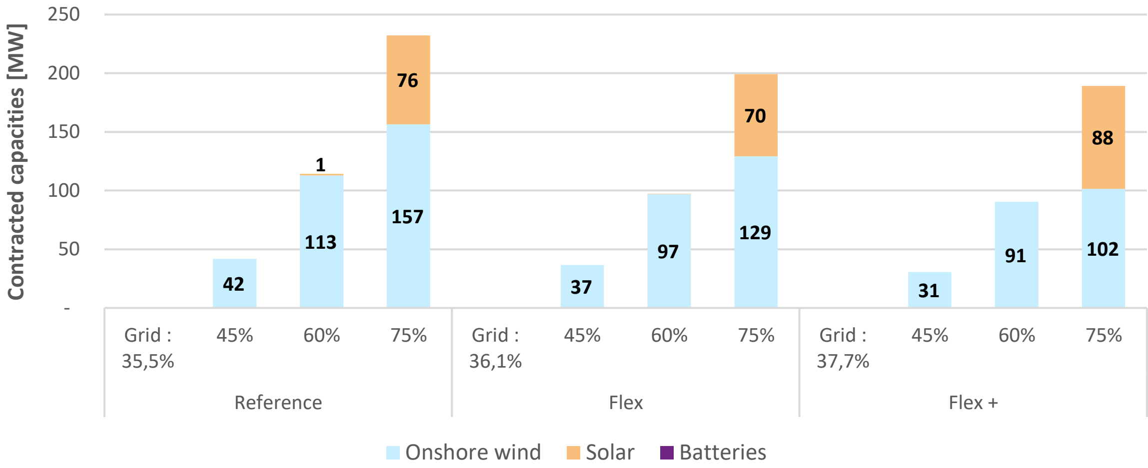

Figure 5 Installed capacities needed to reach three RE score objectives by 2050, according to the charging flexibility scenario

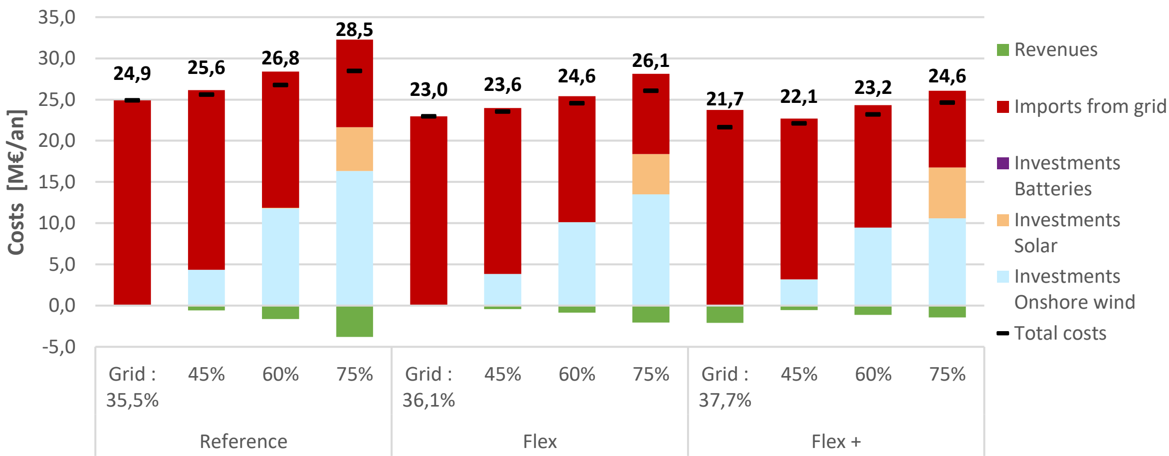

Figure 6 Supply costs for different RE score objectives and charging flexibility scenarios, for 2030

2.2 Achieving a 100% RE score is very complex

The capacities required to achieve RE scores of 90%, 95% and 100% (the city's 2050 target) for the 2050 "Low RE" scenario are shown in Figure 7[14]. Achieving higher RE scores requires contracting with more renewable capacity and limiting imports from the national grid, which has a significant share of nuclear generation (around 35% of the French mix in 2050 for the "Low RE" scenario).

Achieving an RE score of 90% would require between 222 and 318 MW of renewable capacity, producing between 78% and 137% of the mobility energy demand (on an annual basis). The required capacities increase rapidly, by +40% to +70% to reach an RE score of 95% and by more than 6 to 9 times to reach an RE score of 100%. Reaching a RE score of 100% requires significantly oversized capacities

[14] Costs are not shown for 2050, as there is high uncertainty and variability in spot prices, which determine the investments profitability.

compared to the mobility demand because it needs to ensure there is enough production at every hour of the year, including the periods of peak demand and, especially, the periods of low renewable generation. **This shows the increasing complexity of ensuring supply from renewables alone for every hour of the year, especially for the last few per cent.**

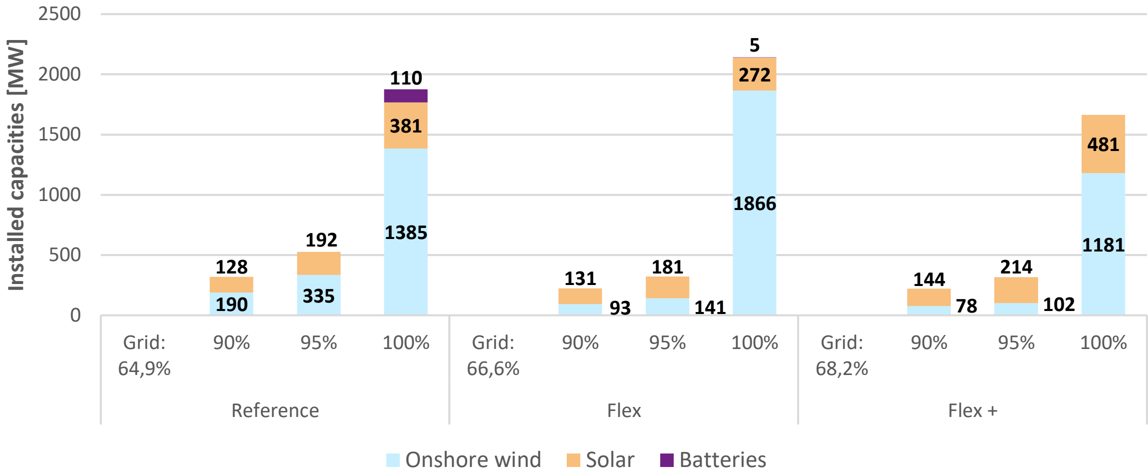

Figure 7 Installed capacities needed to reach three RE score objectives by 2050, according to the charging flexibility scenario

2.3 Key results on socio-economic and environmental impacts

The following socio-economic and environmental impacts associated the electrification of mobility in the different scenarios modelized (Reference, Flex and Flex+) were assessed:

- Socio-economic impacts:
  - Job creation
  - Gross value added created
- Environmental impacts:
  - Climate change
  - Land artificialization
  - Biodiversity
  - Pollution / Human health

This assessment was conducted by considering the entire life cycle of the different electricity generation technologies (solar, wind, fossil-based technologies) used in the modelled scenarios.

Regarding job creation, our results tend to show that for the deployment of new RE generation capacity by 2030, for all the scenarios modelled, most of the jobs created are related to the deployment of wind energy. Also, in an expected way, scenarios involving the deployment of the largest RE capabilities generate the most jobs, i.e. under the Reference scenario more than in Flex and Flex+ scenarios.

As for the value added created, our results demonstrate that renewable energy is a major generator of added value in France. In fact, a significant proportion of investment and operating expenditure is localised and cannot be relocated. Employment is the main beneficiary of this economic activity, with salaries accounting for around 50% of the value added. However, the importance of relocating the industrial production of equipment (components, assembly of PV panels and wind turbines) would increase the value added in France.

Our assessment of impacts on climate change shows that the development of wind and solar energy production is also a lever for reducing greenhouse gas (GHG) emissions, as these technologies emit 75% and 20% less GHG respectively than the average French electricity mix in 2021 (56gCO2eq/kWh).

Regarding impacts on climate change, our analysis of the GHG emissions of the various scenarios for the 45% and 75% RE objectives highlights the fact that the use of wind and solar power will make it possible to drastically reduce the GHG emissions associated with the electricity generation phase. Furthermore, an analysis of the entire life cycle of electricity generation by means of production also shows that the use of renewable energies (solar and wind) poses a key decarbonisation challenge in terms of reducing the carbon intensity of equipment production. As shown by the comparison of emission factors for electricity produced from PV manufactured in China, Europe and France, relocating the industrial production of equipment (components, assembly of PV panels and wind turbines) would make it possible to achieve significant reductions in the carbon intensity of these means of electricity production.

For other environmental impacts assessed, it should be noted that renewable energy technologies allow to avoid or reduce certain negative environmental externalities related to the use of fossil fuels for electricity generation. As a matter of example, the impacts related to the landfilling of nuclear waste, whether considering soil artificialization, biodiversity or human health can be avoided through the use of renewable energies.

However, the use of wind and photovoltaic is not environmentally neutral and may have significant impacts depending on the nature and characteristics of the projects considered (geographical location, size of the project, choice of equipment, etc.). In terms of biodiversity, the use of onshore wind can have adverse effects on surrounding bird populations. Also, the use of many substances harmful to human health and ecosystems for the manufacture of photovoltaic infrastructure and equipment is a significant impact on the issue of pollution and human health.

3 Analysis of the City-owned fleet

The City's fleet considered for this modelling task is composed of a total of 3464 vehicles, 20 % of which are powered by a low-carbon engine (including battery electric vehicles, hydrogen and bio-NGV) in 2022. The vehicles were divided into six categories which are presented in Figure 8:

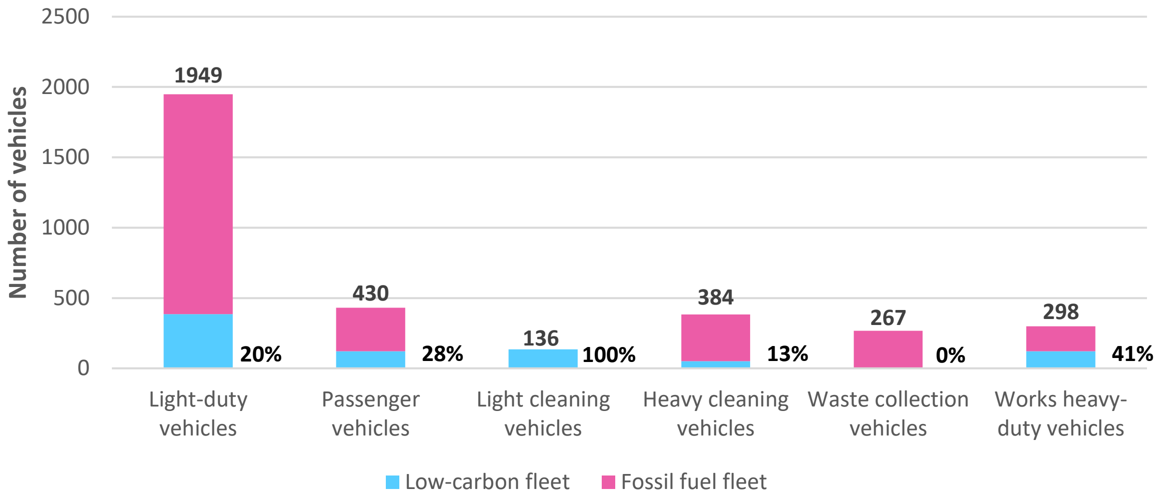

Figure 8 Number of vehicles owned by the City of Paris in 2022 per type of vehicle

The light-duty vehicles represent a major part of the City's vehicles with 56% of the vehicles while the other categories vary between 4% and 12% in relation to the considered fleet. The light cleaning vehicles[15] and the works – heavy duty vehicles have the highest shares of low-carbon engines (100% and 41% respectively) in contrast to the waste collection vehicles which do not have for the moment any low-carbon engine.

3.1 Demand scenarios

Two demand scenarios were built in order to take into account the uncertainties in the usage and evolutions of the City's fleet:

- **Low needs** scenario represents the lower bound for the charging demand projections. This scenario reflects a low range for vehicle usage (lower kilometres driven, or lower energy needs per session), as well as a reduction of the number of vehicles for certain categories (light-duty vehicles, passenger cars and garbage trucks).
- **High needs** scenario represents the higher bound for the charging demand projections. This scenario considers an intensive usage of certain vehicles, as well as a constant size of the City's fleet from 2022 up to 2050.

For this work, only the mileage data for light-duty vehicles was available from the City of Paris. Actual consumption data (e.g., mileage, oil consumption, electricity consumption from City-owned charging points) for other types of vehicles was not available, due to a lack of measurement by the City. The

[15] Mostly operator-handled vacuum cleaners, such as these.

parameters reflecting the usage patterns (mileage, consumption) of other types of vehicles were estimated by the consultants.

3.2 Electric mobility needs and RE scores

The electric mobility needs of the City's owned fleet are expected to increase due to the massive electrification of the fleet by 2030 and 2050 as it is shown in Figure 2[16]. The charging needs increase from between 1.4 to 3.2 GWh in 2022, to 7.5-18.5 GWh by 2030. By 2050, the charging needs range between 5.7 to 18.8 GWh. The wide range of charging needs reflects the uncertainty on vehicle usage and its evolution.

The charging demand from the City-owned fleet can represent, at most, 4.2% of the total electric mobility demand in Paris (around 450GWh for 2030 and 2050, see report for Task 1 and 2), and less than 0.15% of the total electricity consumption of the City of Paris (13TWh in 2021).

The charging needs are mostly from heavy cleaning vehicles (such as street sweepers) and garbage trucks[17]. These are heavy-duty vehicles, with high consumption rates, and as part of the core public services provided by the City they are used (almost) every day. Work vehicles (such as tractors or tool carriers) also represent an important share of the charging needs; however, their use is expected to be less intensive than cleaning vehicles. Light-duty vehicles (such as delivery vans) and passenger cars represent a lower share of the charging needs, and the number of these vehicles in the City's fleet can decrease in the upcoming years, as they move to other mobility uses (such as cargo-bikes).

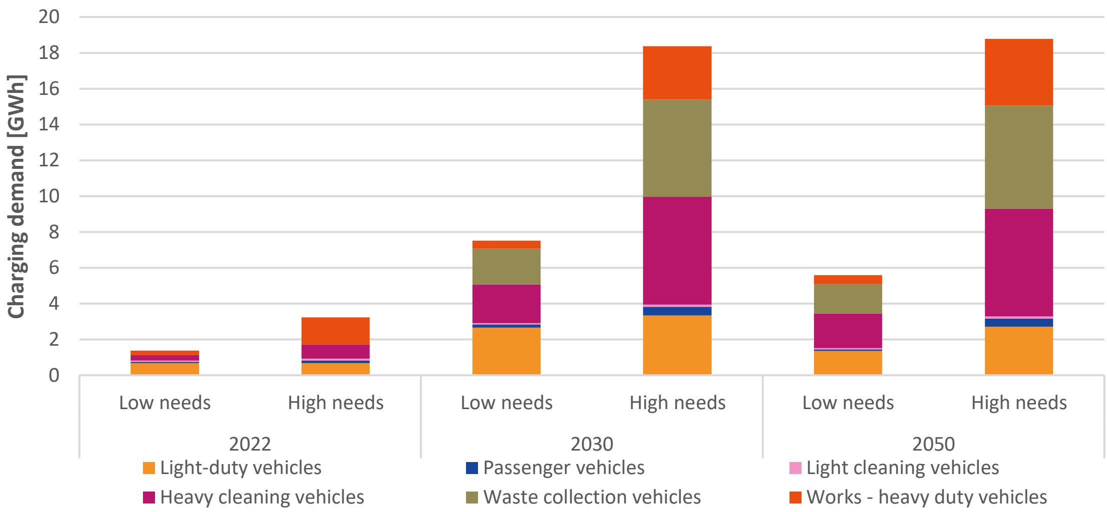

Figure 2 Charging demand of the City's fleet by 2022, 2030 and 2050 for the consumption scenarios

The hourly charging profiles were generated for an **uncontrolled charging scenario** and then the RE scores computed, based on the projection of charging needs and with hypothesis the schedules and

[16] Most categories are expected to be fully electrified already in 2030, with the exception of works heavy-duty vehicles and waste collection vehicles which are expected to have a slower electrification pace.

[17] Only the City-owned garbage trucks were considered. They represent around half of the total garbage trucks operating in Paris, and ensure the garbage collection in 10 out of 20 *arrondissements*. The rest is operated by private contractors.

charging patterns for each vehicle category. The RE scores of the City-owned fleet are close to the average grid RE factor as can be seen in Table 1, in line with the findings of Task 1. The RE scores of the "Low needs" scenario are in average 2% higher compared to the High needs scenario. This is due to a higher share of charging sessions occurring during the night where the grid RE factors are lower.

Table 1 RE scores for the City's owned fleet for the two demand scenarios by 2022, 2030 and 2050

Year	Average Grid RE factor	RE scores	
		Low needs	High needs
2022	27%	29%	27%
2030	35%	35%	33%
2050 – Low RE	63%	64%	62%
2050 – High RE	84%	85%	84%

As for all of the City's electric mobility, the supply coming only from the grid does not allow to reach the City's objectives (45% by 2030 and 100% for 2050). Therefore, additional dedicated investments in renewable and flexibility sources would be needed to further boost the RE scores.