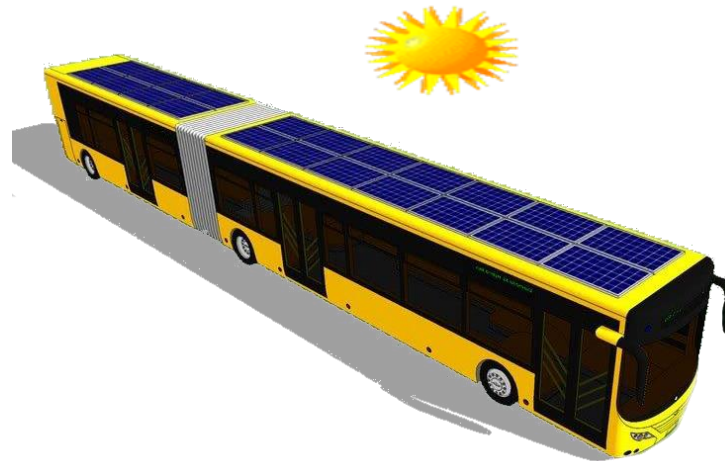




Shading losses measurements for integrated photovoltaics potential estimation for solar city bus and data-driven simulations



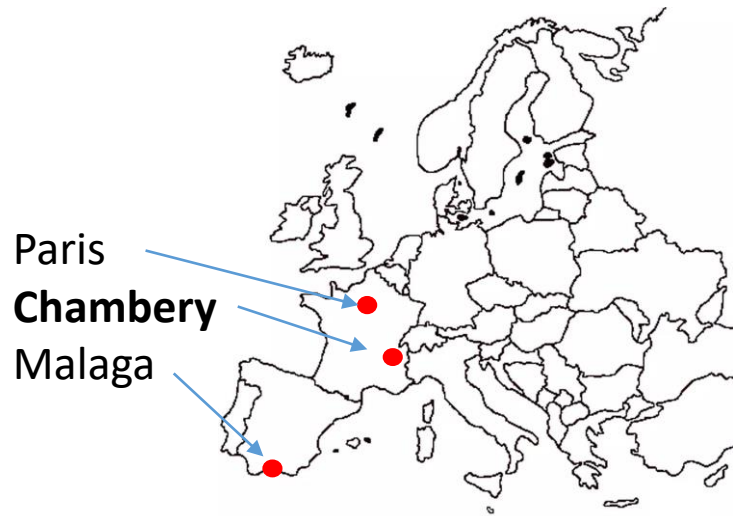
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CEA LITEN - Campus INES**

- Objectives
- Energy and mileage modeling , methodology
- Shading losses measurements on vehicle
- Simulation results
- Life Cycle Assessment methodology and results
- Conclusions and next steps

- Primary energy saving / reduce greenhouse emissions → Vehicle Integrated PhotoVoltaics has ongoing interest
- Exploring the potential of VIPV in term of PV used energy, mileage and avoided CO₂ emissions
- Give conclusions and recommendations to reach an influence on climate change (positive CO₂ balance)
- Case study : solar city bus in Europe
 - ✓ Best potential for PV surface on Wh/km ratio
 - ✓ Use case in good accordance with solar period (day time)



City bus parameters

Available PV surface
Battery nominal energy
System efficiencies
Electrical consumption
Shading losses
Frequency of recharge with the grid

Inputs Time series

Monthly solar energy
Distribution of solar irradiance
Use profile

Mathematical model

Calculations for 365 days
Energy balance within ¼ h time step
Battery state of charge

Outputs

Annual PV energy
Annual mileage with VIPV
Daily distance with VIPV
Battery state of charge profiles

Simulation parameters and assumptions



- **Projections in 2030**
- **PV:** 27 m², 230 W/m²,
Ageing: -2 % first year then -0.7 %/year → **5.7 kW at midlife**
- **Battery :** 440 kWh
- **Consumption :** 880 Wh/km and 400 W during standby

➤ System efficiency and extra consumption for using PV

Direct charge in main battery: 93 %, extra consumption for using PV: 26 W parking and 12 W during grid charge and driving

Via 48 V auxiliary battery: 89 %, periodic wake-up every 100 Wh with consumption 8.5 Wh, 12 W extra consumption

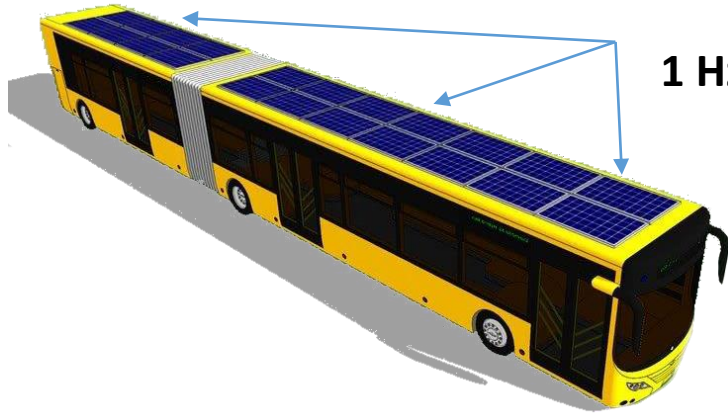
➤ Use profile :

- 5am-9pm, 6 days per week
- 48 weeks per year
- 40700 km/year
- 200km/day

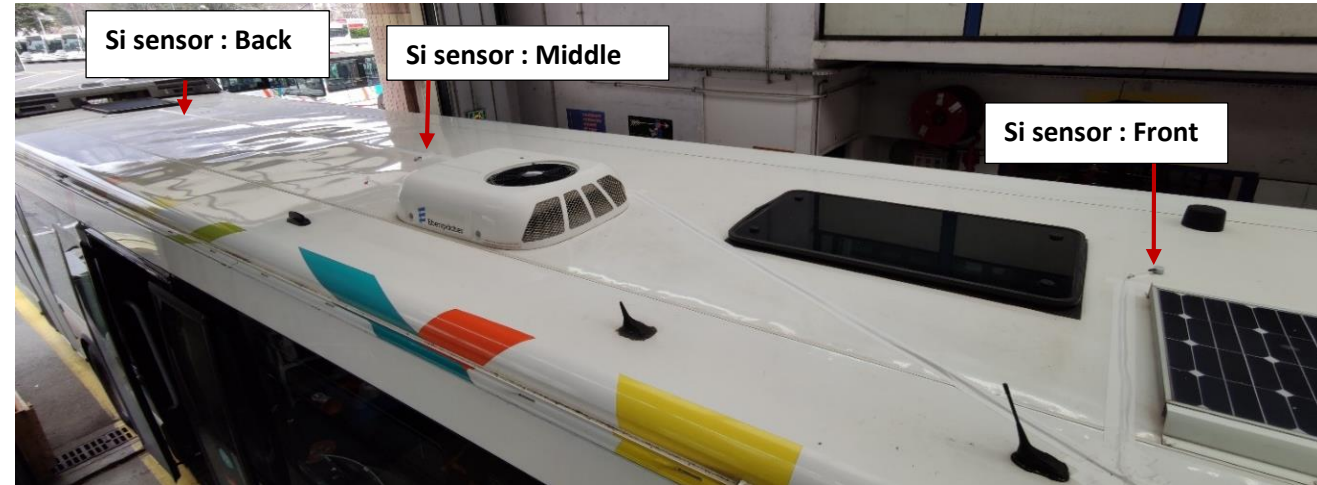


Shading losses: 0 %, 10 % and 30 % + measured values



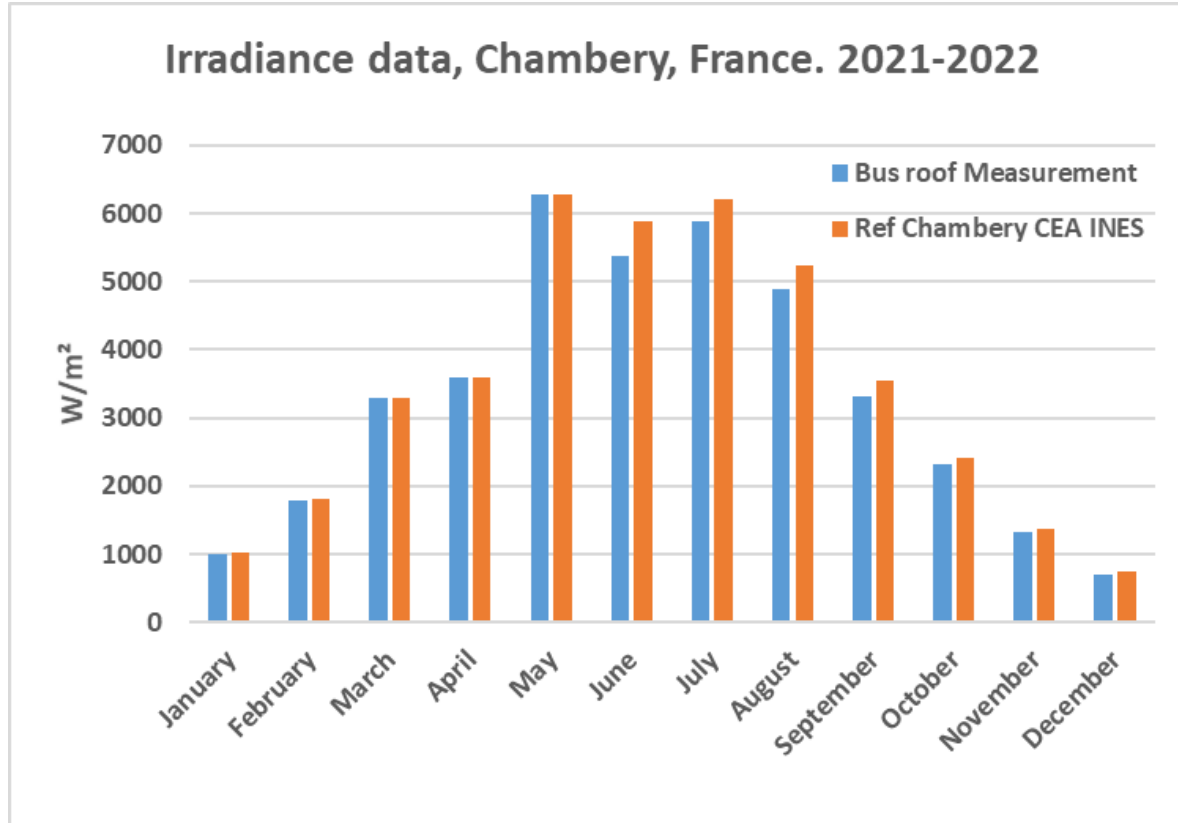


3 sensors installed
GPS location
1 Hz recording (data logger)



Example of bus trip

- Measurement configuration:
 - City bus, 200 km/day, from 5am → 9pm
 - Average of 3 sensors data to take into account the shading influence
 - Data comparison to CEA INES reference sensor (10 km distance)



	Shading loss (%) for simulation	nb of measurement days
January	1,4	6
February	0,75	8
March	0,1	9
April	0,1	10
May	0	25
June	9,2	50
July	5,7	44
August	7,2	44
September	6,72	45
October	4,61	43
November	2,5	21
December	4,75	33
Annual	3,6	

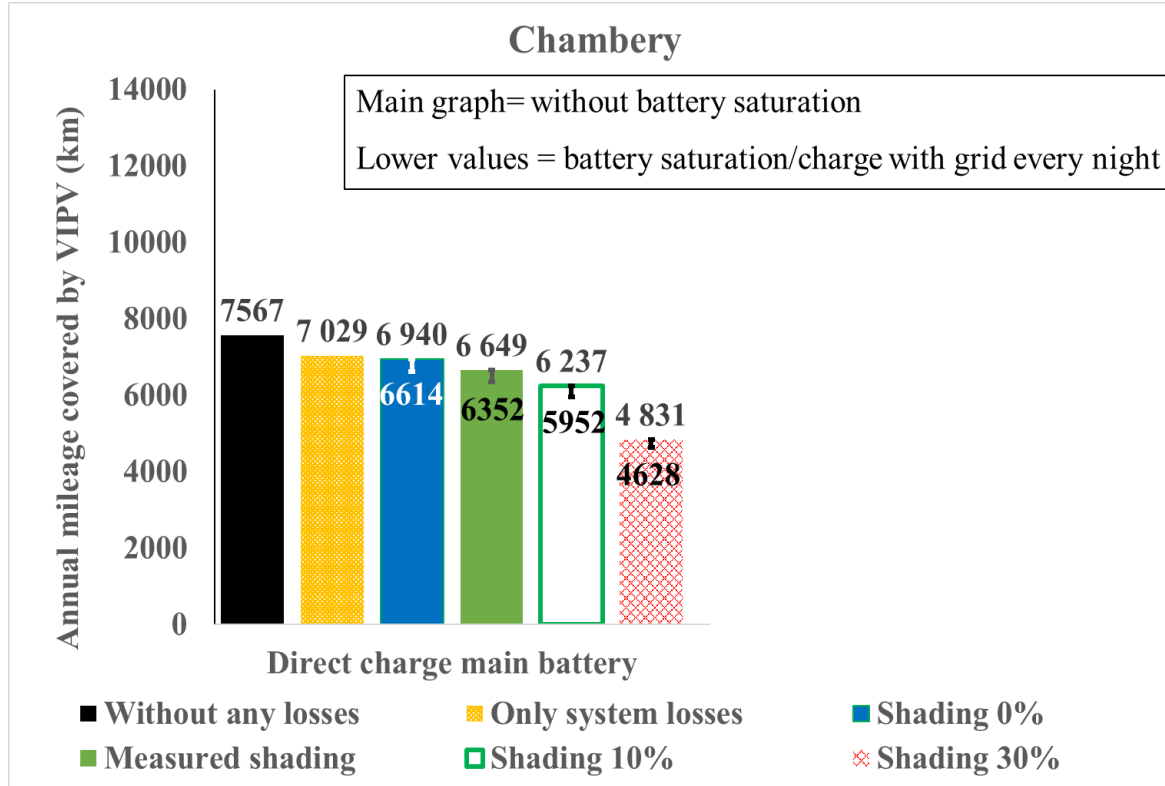


Inputs for
simulation model



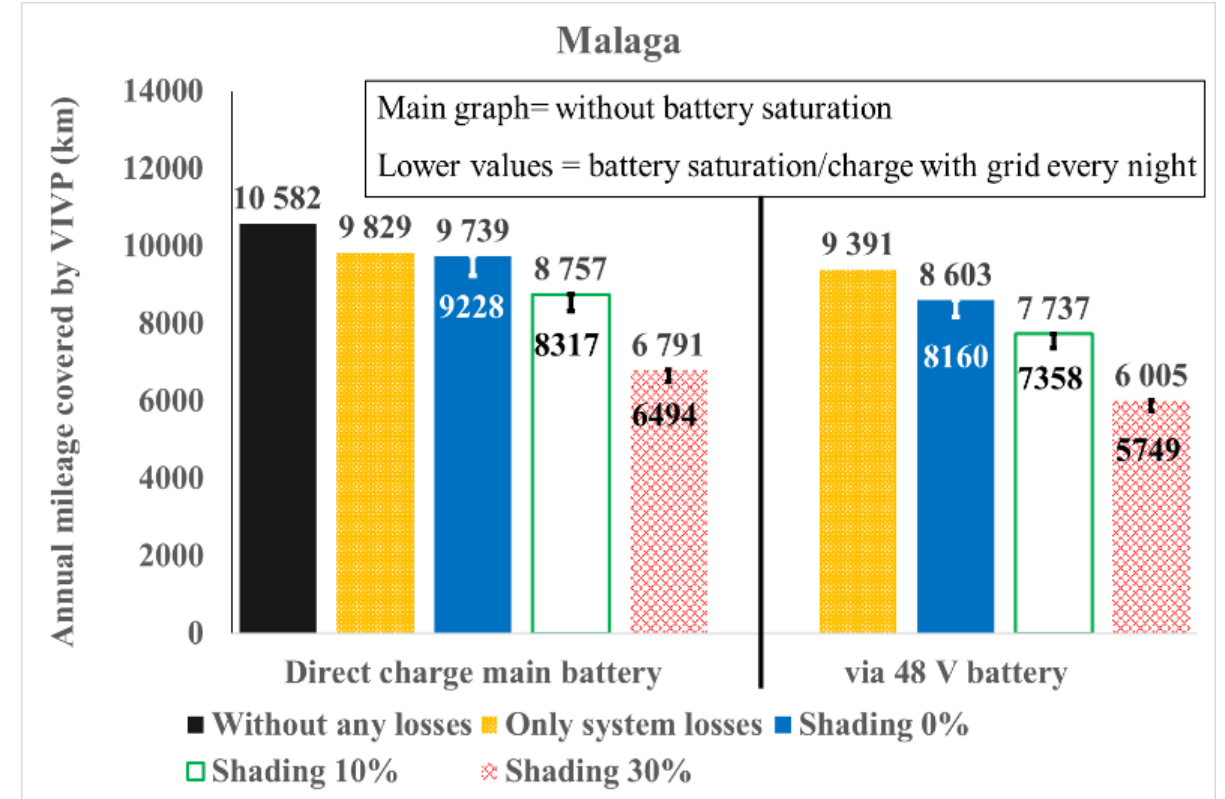
Measurement robustness
appreciation

Chambery, France: 4105 – 6940 km



➔ 9 % - 15 % of the annual total distance

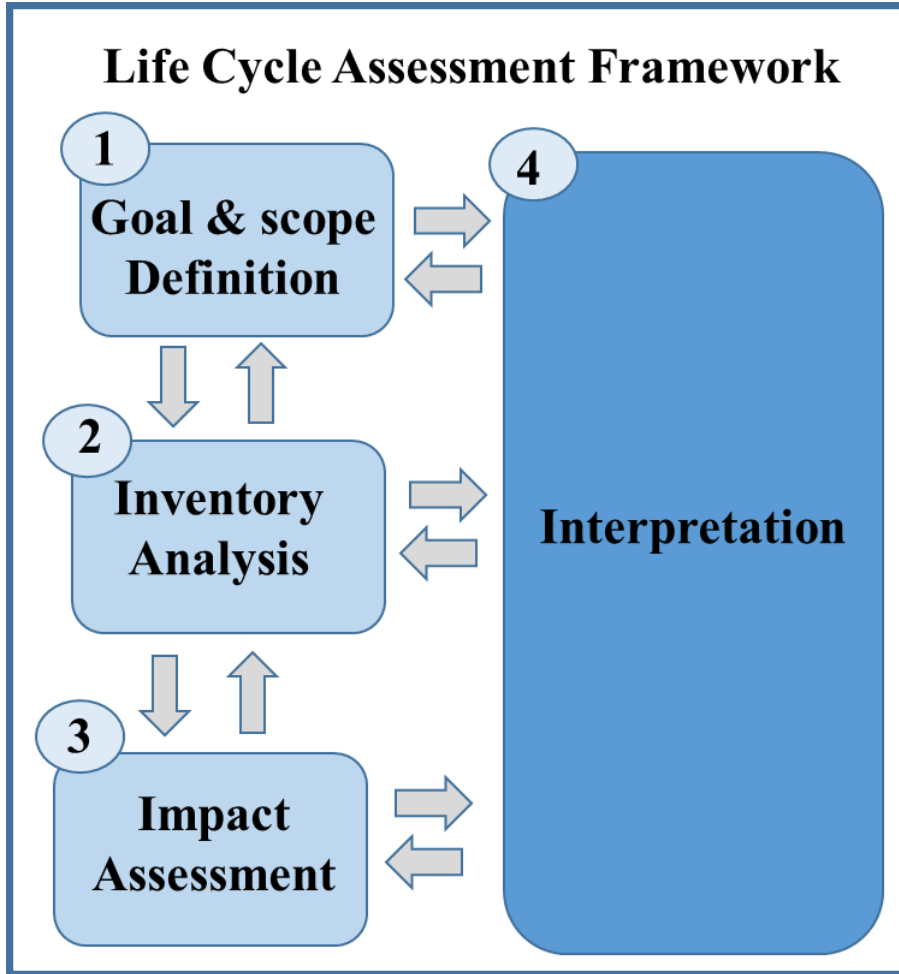
Malaga : 5749 - 9739 km



➔ 14 % - 24 % of the total annual distance

➔ Direct charge in main battery > charge via 48 V battery

➔ Location > Shading > electric architecture > battery saturation



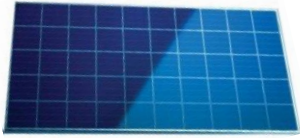
$$\text{Balance (kg CO}_2\text{-eq scenario)} = \text{avoided impact} - \text{manufacturing balance}$$

PV production = avoided impact on the electricity grid

Carbon balance manufacturing = X kg CO₂-eq

➔ End of life of solar roof : not considered

Life cycle assessment assumptions

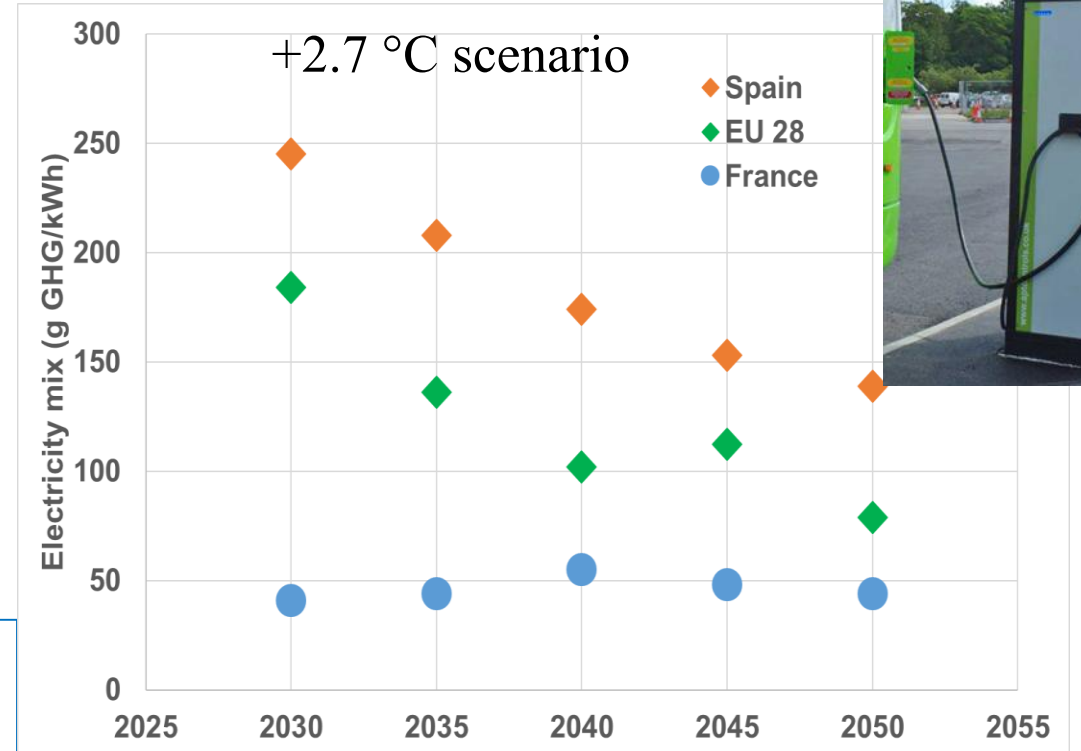


- ✓ Technology: PERC+
 - ✓ Poly silicium : Germany
 - ✓ Lingot / wafer: Norway
 - ✓ Module: France (GBS, no frame)
 - ✓ Manufacturing: projection in 2030
- Low carbon**



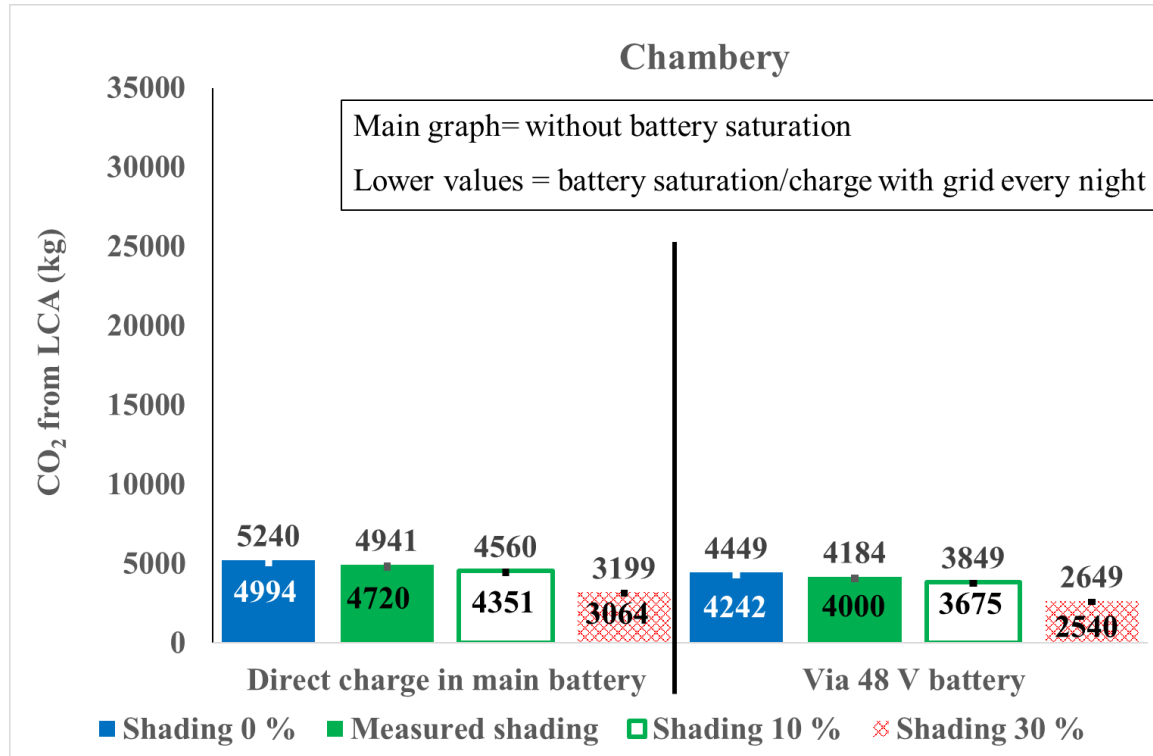
- ✓ Life time: 20 years / 814 980 km (commercialized in 2030)
- ✓ Weight: 26000 kg
- ✓ Taking into account the overweight of the PV integration :
+1 % overweight → +0.5 % electricity consumption

Electricity mix



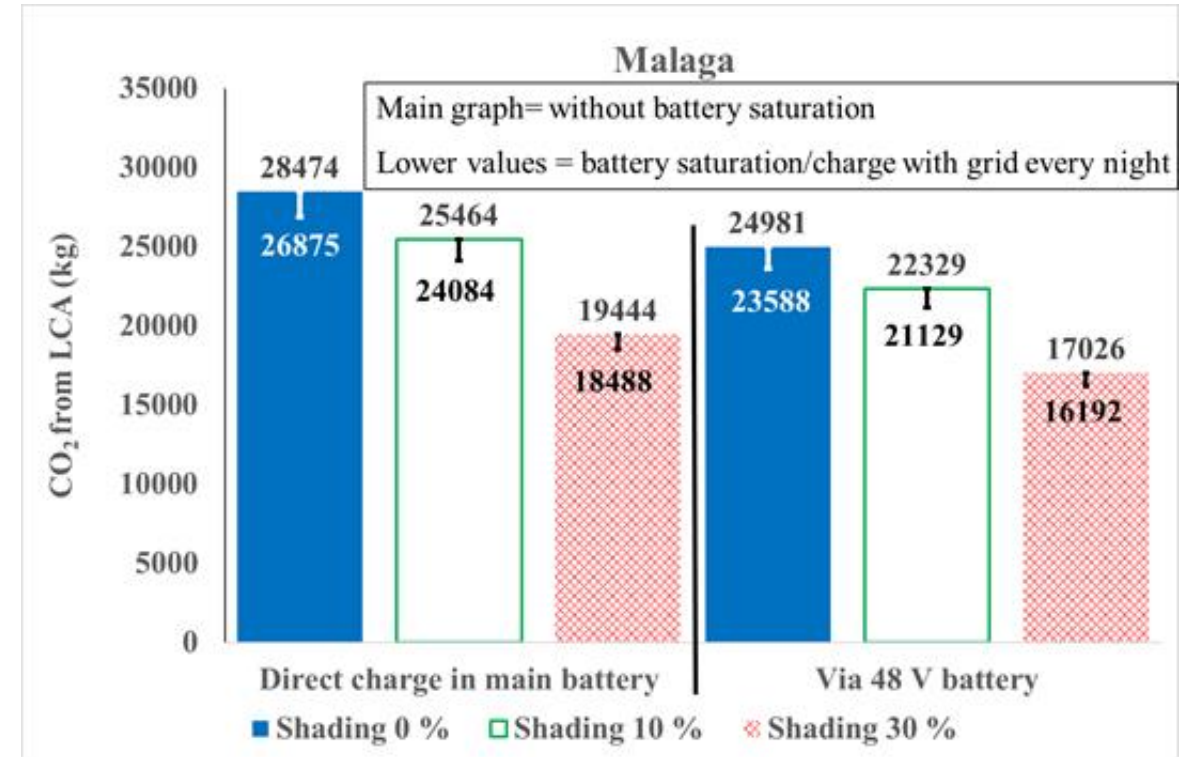
City bus life

Chambery: 2.5 – 5.2 T CO₂-eq



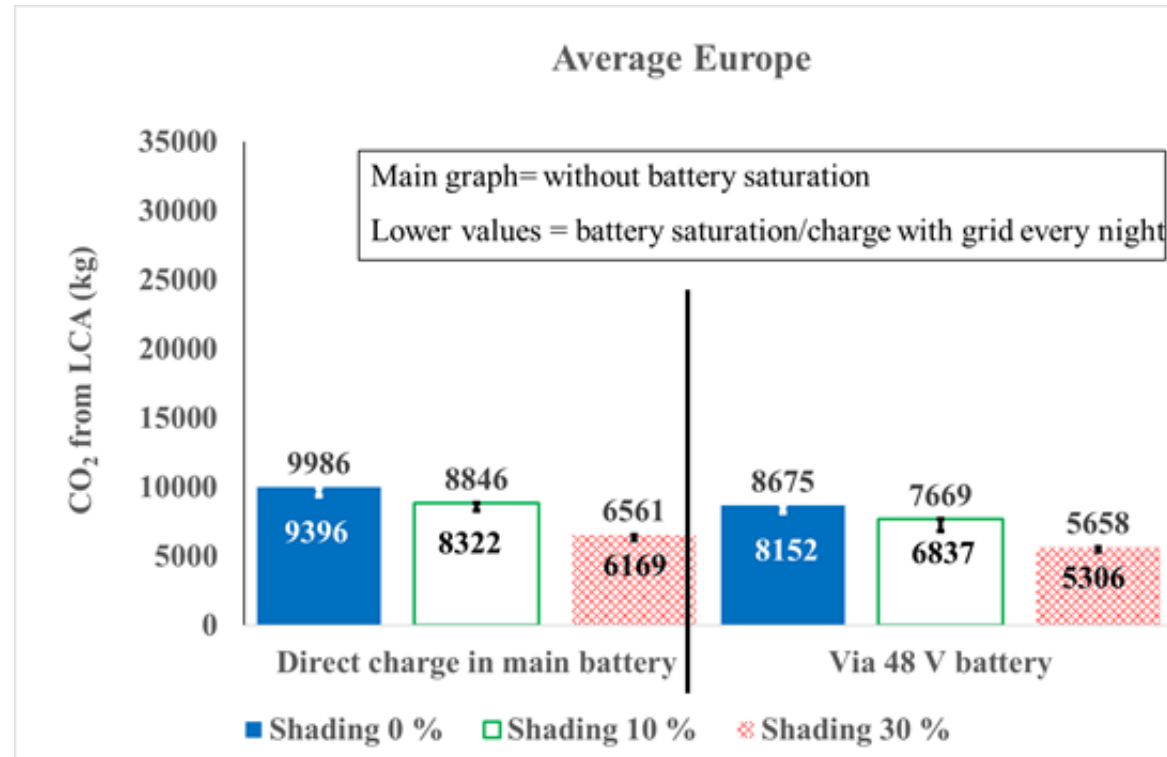
France scenario for carbon electricity mix
50 g CO₂/kWh

Malaga : 16.2 – 28.5 T CO₂-eq



Spain carbon electricity mix
183 g CO₂/kWh

Average Europe : 5.3 – 9.9 T CO₂-eq



Average in term of solar irradiance (Paris) **and** electricity mix (122 g CO₂/kWh)

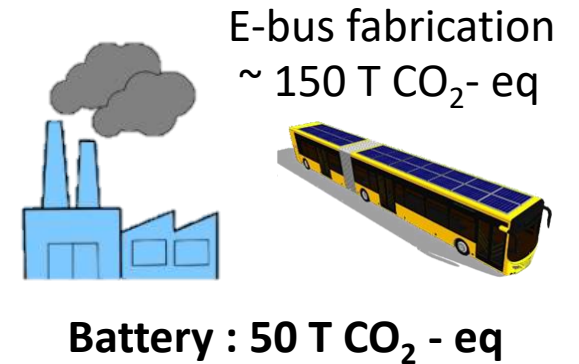
- City bus use case (2030→2050)
- Simulation tool of useful PV energy, coupled with shading measurements (**annual shading 3.6%**)
- Parameter influence on City Bus : location > the shading losses > electric architecture > battery saturation
- Architecture with direct charge of the high voltage battery is better for city bus
- European best case:
 - up to **9739 km** annual mileage covered by VIPV (**24 %** the total distance), up to **47 km/day**.
- Average Europe (Paris):
 - up to **6269 km** annual mileage covered by VIPV (**15 %** the total distance) and up to **35 km/day**.
- Chambéry
 - up to **6940 km** annual mileage covered by VIPV (**17 %** the total distance) and up to **41 km/day**.

- With +2.7 °C climate change electricity mix scenario : solar city bus vs e-bus
 - ✓ Solar average Europe + Europe electricity mix → up to 10 T CO₂-eq
 - ✓ Solar average Europe + low carbon electricity mix → up to 5 T CO₂-eq
 - ✓ Solar best case Europe + high carbon electricity mix → up to 28 T CO₂-eq

- With decarbonized electricity mix, VIPV = limited impact.

- **Next steps : Real bus VIPV experimentation with entire system prototype**

- **Up Coming:** two other papers:
 1. VIPV on passenger car : **effect of the thresholds** due to extra consumption with several PV peak power and use conditions
 2. VIPV on light VAN with several use profiles



Lie, K.W.; Synnevåg, T.A.; Lamb, J.J.; Lien, K.M. The Carbon Footprint of Electrified City Buses: A Case Study in Trondheim, Norway. *Energies* 2021, 14, 770.
<https://doi.org/10.3390/en14030770>



THANK YOU!

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