Solar-electric buses for a university campus transport system

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Abstract

This study explores the prospect of replacing conventional university campus buses powered by fossil fuels with electric ones using primarily solar energy stored in batteries and secondarily the central electricity grid. On the basis of existing infrastructure and facilities in the NTUA campus in Athens (Greece), three scenarios are developed for the collection and use of solar energy for electric buses: (a) bus stop shelters covered with solar panels, (b) installation of solar panels in unused open spaces, and (c) solar roads, i.e. specially engineered panels that can be installed on the road surface. Since the availability of solar energy is linked to sunshine levels, we employ GIS mapping technology to select the locations with the highest solar radiation. For each of the three scenarios, we investigate the optimal technical configuration, the resulting energy generation and the capital cost. The preliminary feasibility analysis shows that scenario (b) presents the lower capital costs in relation to energy generation. Therefore, we further explore this scenario by simulating its daily operation using historical solar radiation data including the actions of buying and selling energy to the central grid, when there is energy deficit or surplus, respectively. Overall, results indicate that, regardless of the high capital costs, solar-powered transportation schemes present a viable alternative for replacing conventional buses at the studied location, yet heavily depend on the choice of Photovoltaic (PV) materials, since capacity factors differ among technologies.

Objectives

This study investigates the potential of replacing conventional university campus buses powered by fossil fuels with electric ones powered primarily by solar energy stored in batteries. Specific objectives include:

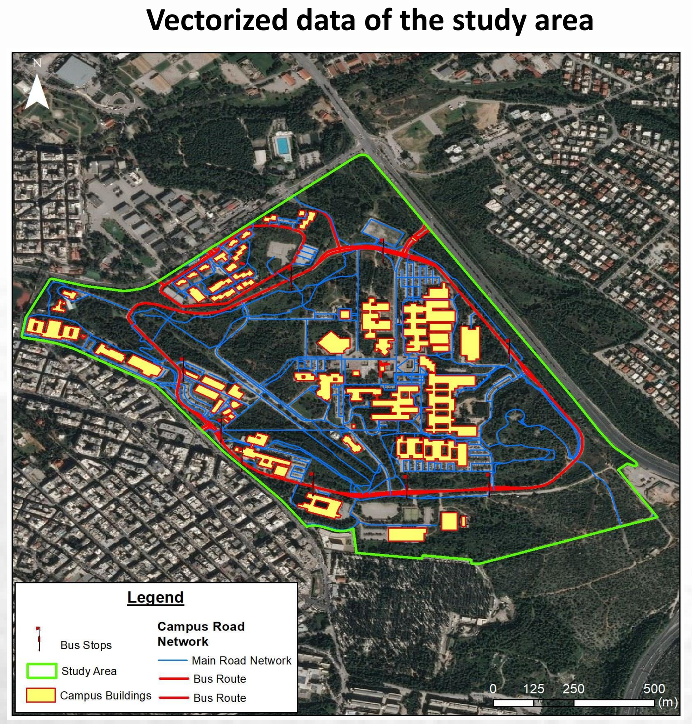
- Investigation of three alternative configurations for solar energy collection
  1. Bus stop shelters covered with solar panels
  2. Solar panels installed at unused open spaces
  3. Solar roads, i.e. specially engineered panels installed on road surface
- Consideration of state-of-practice in electric bus networks (opportunity, inductive, overnight charging)
- Simulation of best scenario using historical daily solar radiation data
  - Profitability and reliability analysis

Data Collection

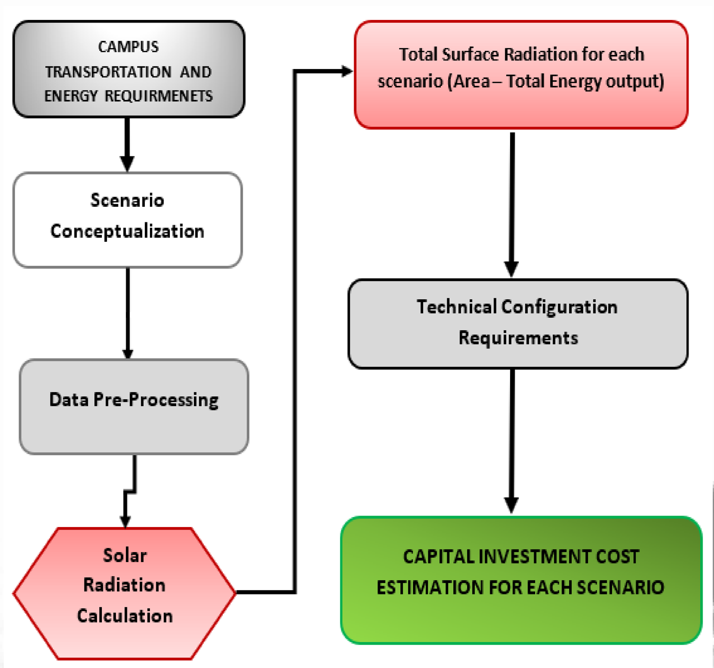
The design of a solar-powered transportation system requires topographic, transportation and solar radiation data. Specifically:

- Route energy demands estimated using average energy consumption value of 1.35 kWh/km
- Route operational characteristics collected through Athens Public Transport Operator website
  - Circular route, connecting the university to subway
  - 19 bus stops, 10 outside the campus
  - 3 buses, 239 days per year, 66 bus trips daily covering a total of 495 km
- Elevation data (Digital Elevation Model - DEM) acquired from Hellenic Cadastre
- Solar panel and electric bus technologies based on data reported from recent literature

Vectorized data of the study area



Study outline



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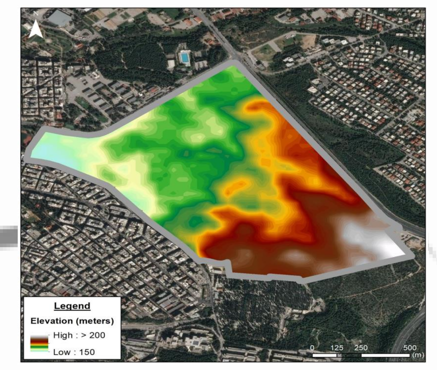
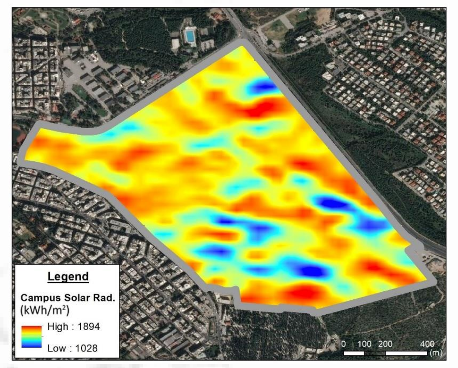
Solar energy estimation



- Solar radiation analysis tool of ArcGIS
- DEM expanded to include adjacent hills that cause shading
- Clearness index equal to 0.6



- Surface solar energy (kWh):

$$S_{sur} = S\,A$$

where S solar irradiance (kWh/m²), A (m²) area of solar panels installed

- Photovoltaic energy generation:

$$E = \mathrm{CF}\, S_{sur}$$

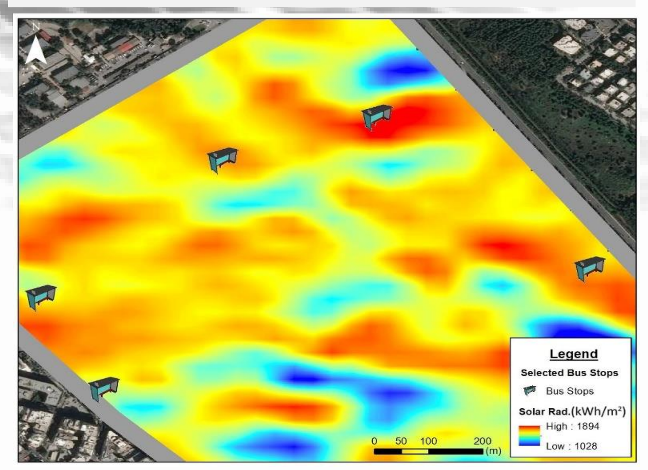
where CF solar panel capacity factor

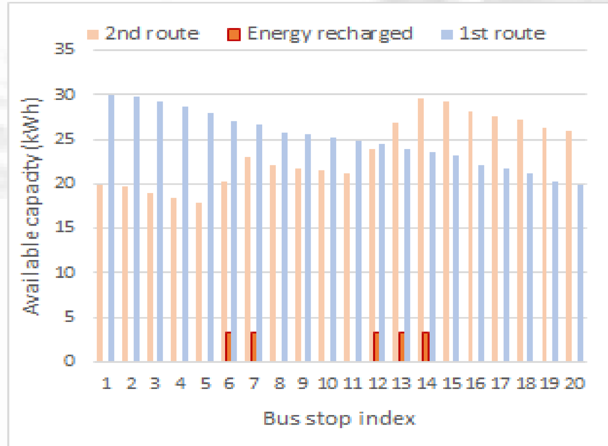
Scenario Analysis

Scenario	Area used (m²)	Direct PV area (A) (m²)	Solar irradiance during days of operation (S) (kWh/m² per year)	Surface solar radiation (S_{sur}) (MWh/year)	Photovoltaic Energy Generation (E) (MWh/year)
1. Solar bus stops	150	105	1109	116	16
2. PV area	3000	2100	1073	2252	315
3. Solar roads	2400	1680	1232	2069	145

- Solar panel CF 14%
- Solar road CF 7%
  - thick protective glass, shading from moving cars, dust
- Area of commercial solar panel 1.93 m²
- Solar bus stop area of 30 m²

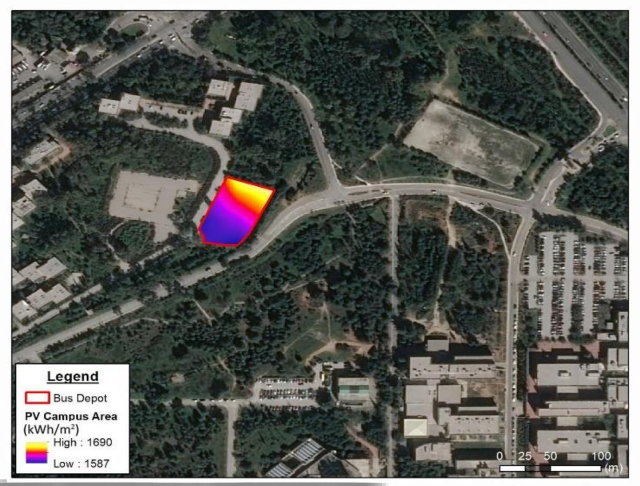
Scenario 1: Solar bus stops





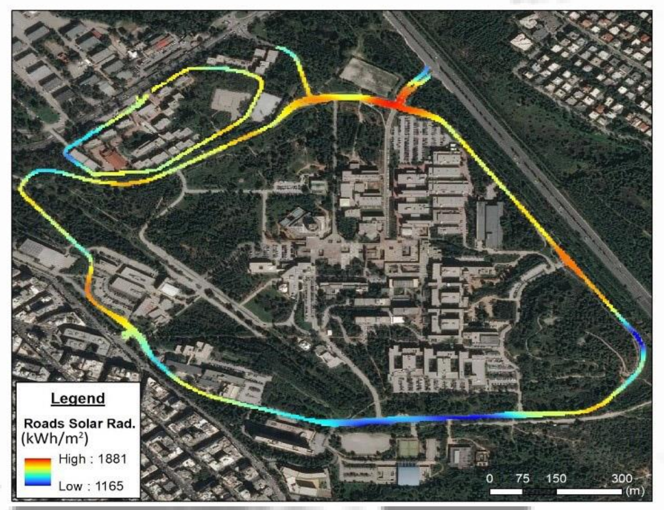
- Opportunity charging
- 5 bus stops with maximum radiation
- 5 batteries of 10 kWh each for storing solar energy at the specific bus stops
- Buses with 30 kWh batteries
- Recharging every 2[nd] trip
- 200 kW power
- 60-second charge during dwell times
- 97% charger efficiency
- 5 chargers required, plus one at terminal
- Supplementary electricity from the grid required

Scenario 2: Open space with solar panels



- Overnight charging
- High-capacity batteries of 700 kWh for vehicles and storing energy
- Open parking area of 3000 m²
- Electric buses with battery capacity of 180 kWh
- 60 kW charger at the depot
- Surplus energy sold to the grid

Scenario 3: Solar roads



- Road segments of approximately 300 m in length and 8 m in width
  - High incoming solar radiation
  - Low shading from buildings and trees
  - Limited traffic
- Buses dynamically powered ~~the~~ as they move using induction
- 4 fast charging devices for the road segments plus one at the terminal
- Buses with 30 kWh batteries
- Small amount of supplementary electricity from the grid required

Preliminary capital cost analysis and scenario comparison

Scenario	Installed PV cost (€)	Vehicle cost (€)	Charger Cost (€)	Bus Battery Cost (€)	Station Battery Cost (€)	Total capital costs per energy unit generated (€/MWh)
1. Bus stops	167,421	1,050,000	1,500,000	72,000	5,000	171,378
2. PV area	1,674,206	1,050,000	20,000	270,000	420,000	10,891
3. Solar roads	4,284,000	1,050,000	1,250,000	72,000	5,000	45,987

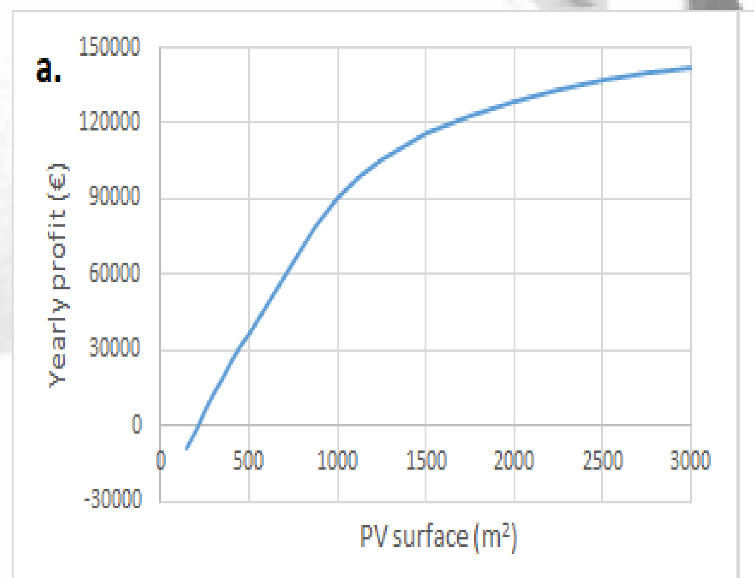
- 350,000 € per bus with 30 kWh
- 250,000 € per fast charger of 200 kW
- Overnight charger of 20,000 €
- 600 €/kWh for high-capacity batteries
- 100 €/kWh for low-capacity batteries
- 4465 €/kW for conventional PV panels

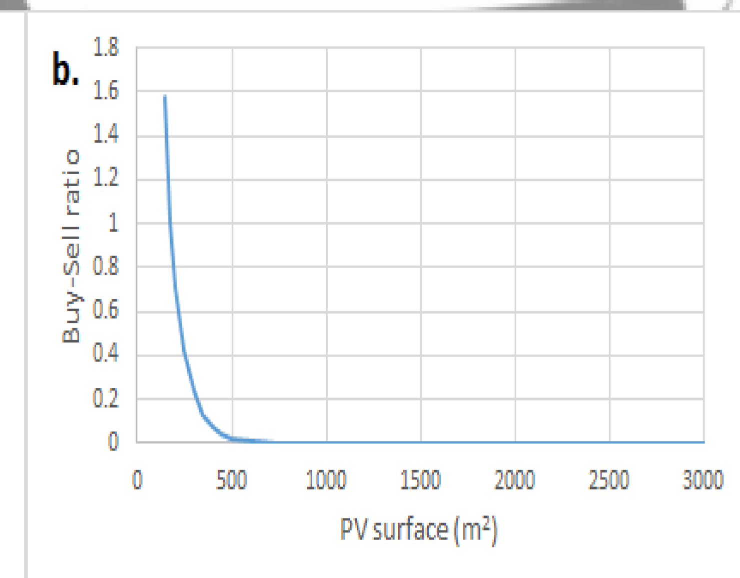
Open space scenario is the most advantageous in terms of capital cost per unit energy generation

- Primary drawback is the sub-optimal exploitation of space -Solar bus stop technology is overly capital intensive at the scale examined
- High capital cost of chargers -Solar road technology suffers from high infrastructure cost and lower capacity factors. Comparison refers to solar energy production

- Larger discrepancies if power transfer efficiency of each charging scheme considered

Simulation of daily operation for open space PV system





- 668.25 kWh daily consumption
- 10-year solar radiation data
- 0.18 €/kWh buy rate
- 0.08 €/kWh sell rate
- System becomes profitable when installed surface exceeds 206 m²
- Nearly autonomous, i.e. 1% buy-sell ratio, at 600 m²

Conclusions

- **In terms of reliability, even a small-scale ground-mounted photovoltaic (PV) installation, e.g. 300-600 m², is a viable option for the given location, depending on the desired degree of autonomy.**
  - **Daily solar energy stored at batteries while buses are charged during the night**
  - **Overnight charging not impacted by diurnal periodicity and fine scale intermittency of solar radiation**
  - **Lower capital and installation costs for PV panels**
  - **Lower cumulative costs for battery and chargers for the electrical buses**
  - **System is profitable even at a small scale (>200 m²), while profits generally rise with the increase of the scale**
- **Great differences are observed in the capital costs of examined solar technologies**
- **Charging scheme employed may be directly related to the solar technology used**
- **Case-dependent advantages related to siting flexibility for the optimal exploitation of incoming solar radiation**
  - **Technologies like solar roads and solar bus stops necessary if open spaces for the installation of solar PV panels are unavailable**

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