

DC TROLLEYGRIDS AS SUSTAINABLE, MULTI-FUNCTIONAL, AND MULTI-STAKEHOLDER ELECTRICAL INFRASTRUCTURES

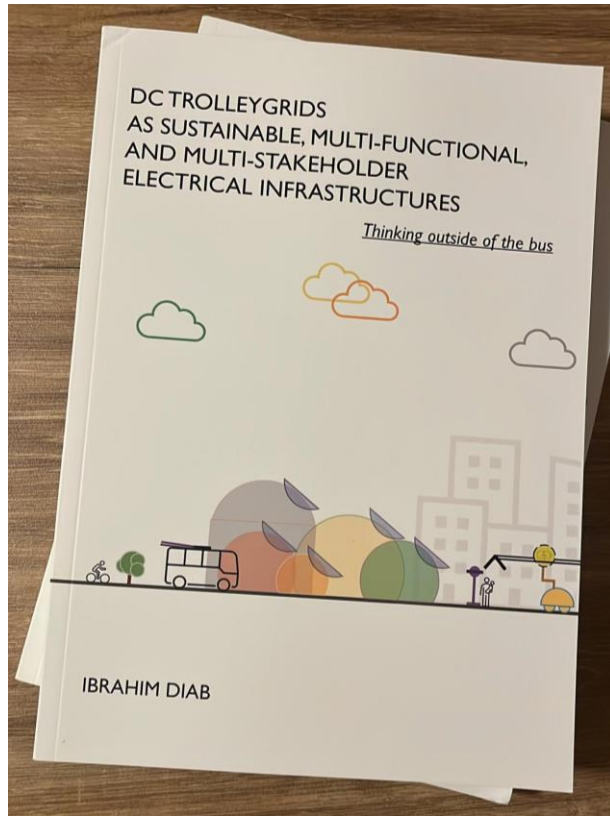
Thinking outside of the bus

Dr. ir. Ibrahim Diab

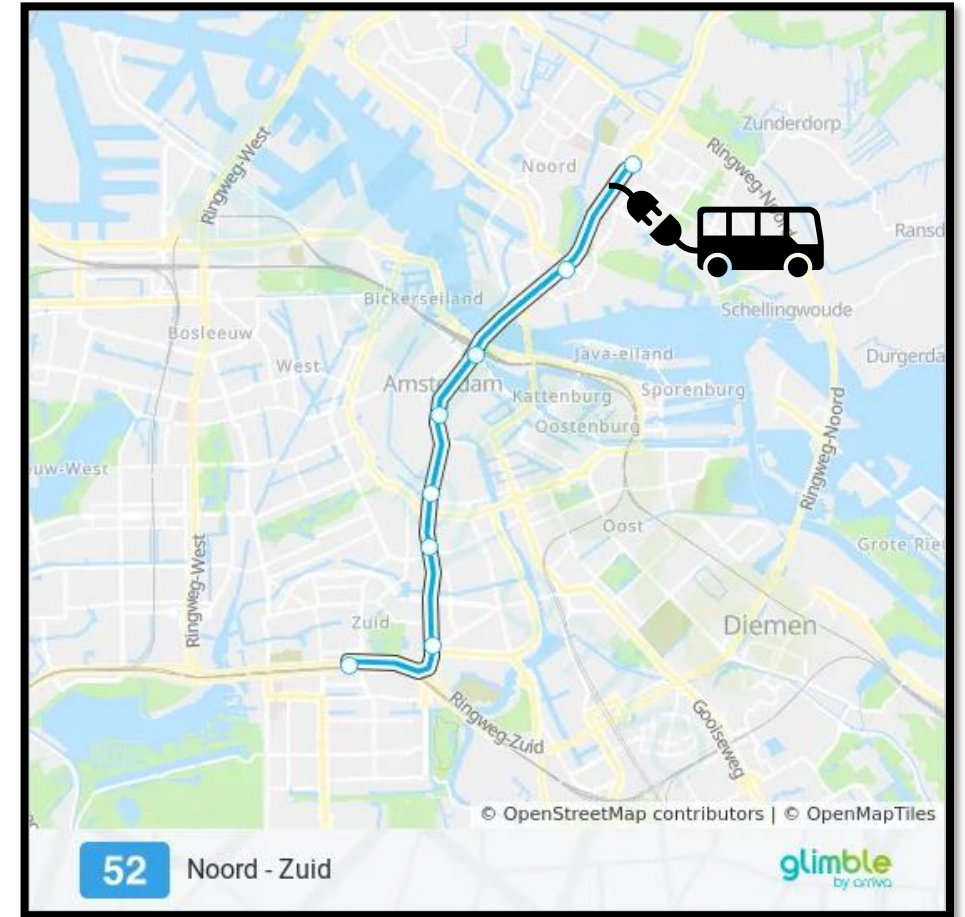


INTRODUCTION

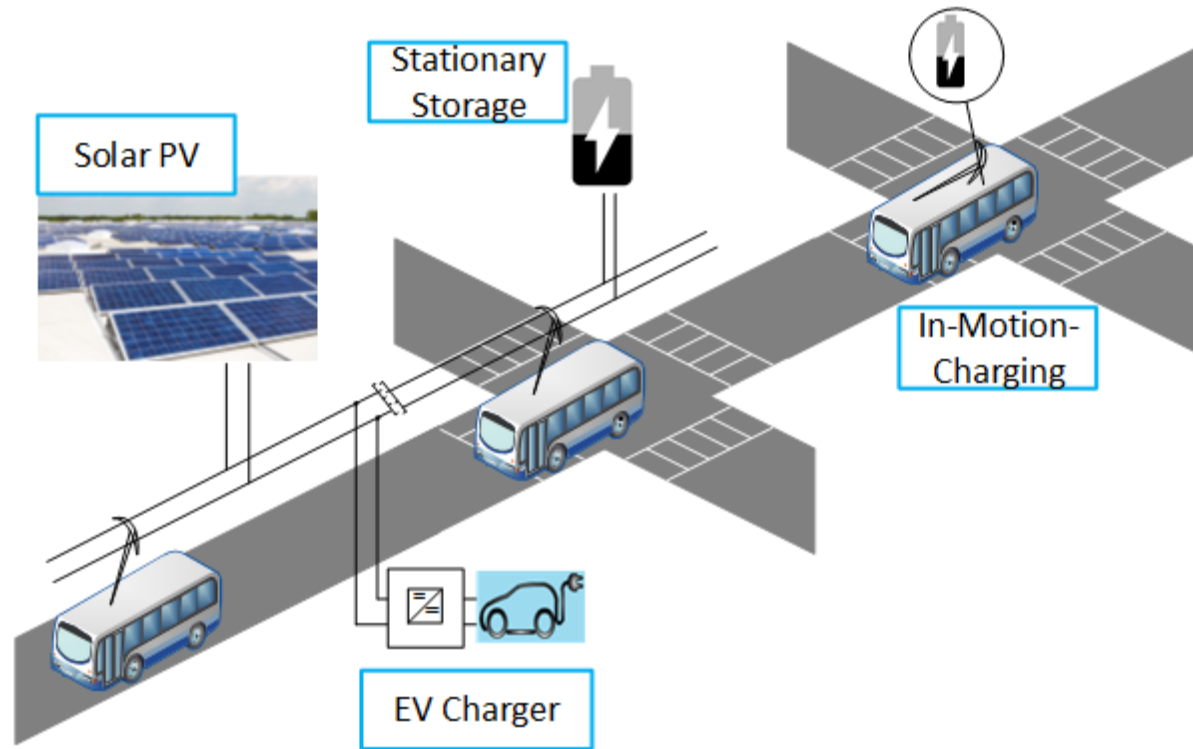
Personal Background



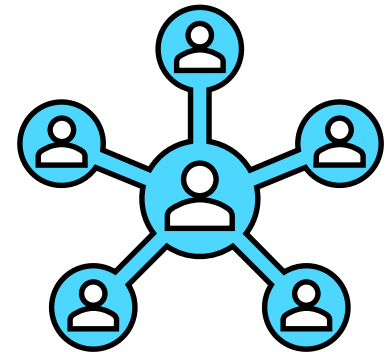
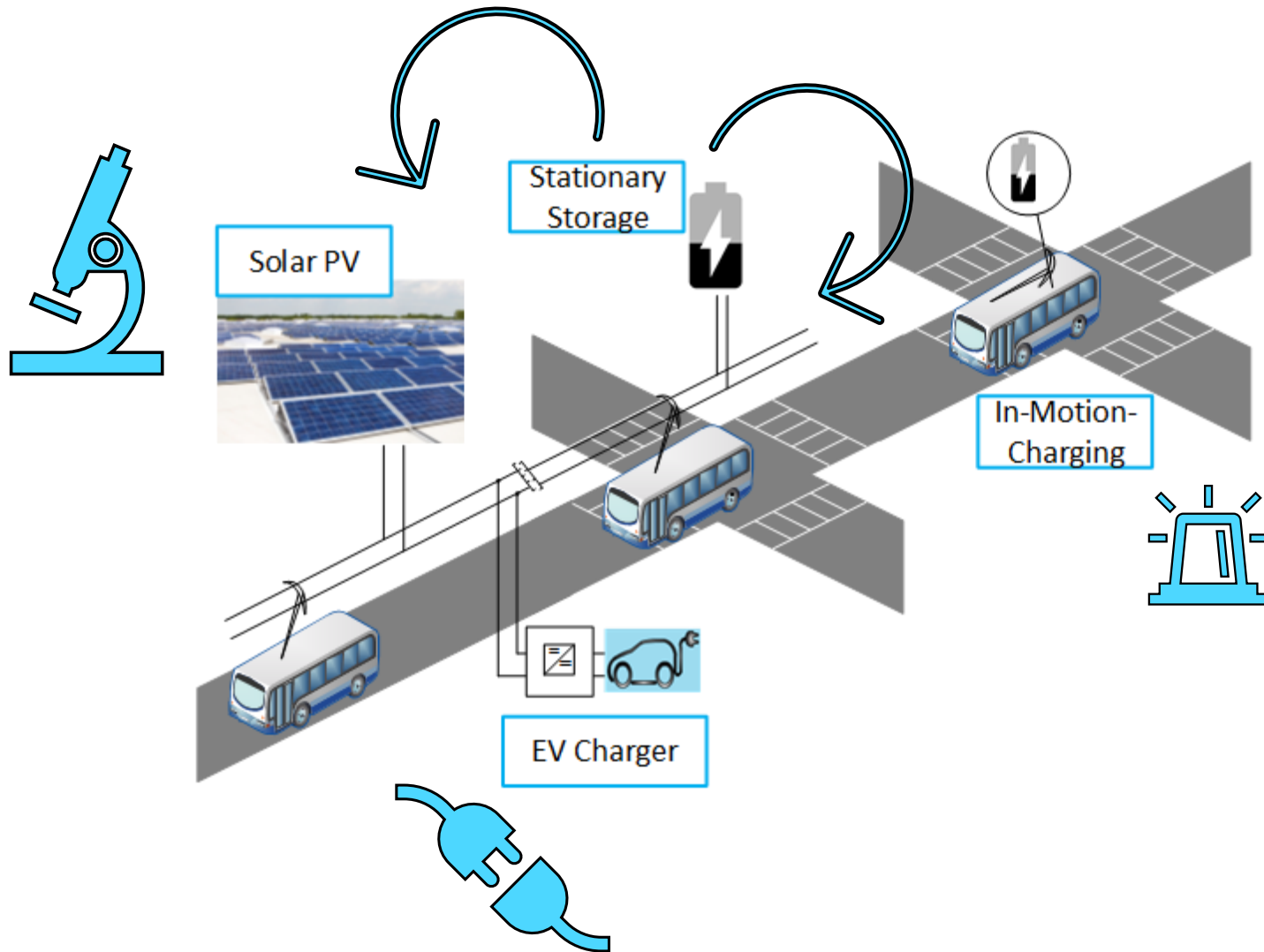
trolley:2.0
for smart cities



The Trolleybus Grid of the Future

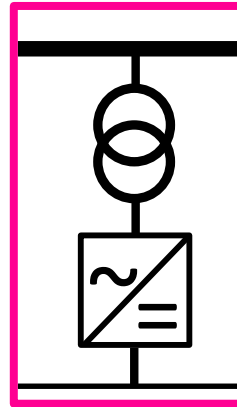
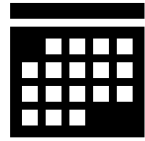
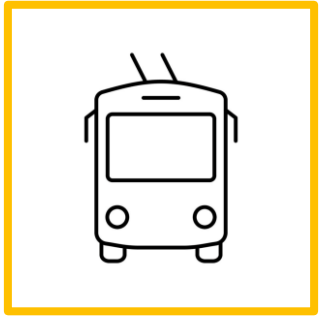


Outline

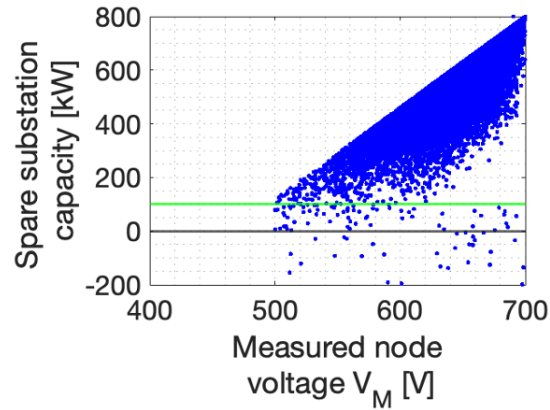


PART I

First Step: Comprehensive Trolleygrid Model

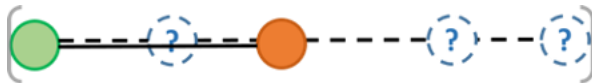


Second Step: Trolleygrid State Estimator



Load at the substation?

Traffic under the section?



$$v_k = \hat{v}, \forall k \neq n$$

For the sake of example, below follows a detailed derivation of Eq. 24 for the case of $n=1$.

$$\frac{\partial V_1}{\partial t} = -\rho(v_1 i_1 + 2v_1 \hat{I}) - \rho[v_1 v_1 v_1] \begin{bmatrix} \frac{\partial i_1}{\partial t} \\ 0 \\ 0 \end{bmatrix} t - \rho[X_{1,0} X_{1,0} X_{1,0}] \begin{bmatrix} \frac{\partial i_1}{\partial t} \\ 0 \\ 0 \end{bmatrix} \quad (26)$$

Leading to:

$$\frac{\partial}{\partial t} V_1 = -\rho v_1 \frac{P_1}{V_1} - 2\rho v_1 \hat{I} + \rho v_1 t \frac{\partial}{\partial t} \left(\frac{P_1}{V_1} \right) + \rho X_{1,0} \frac{\partial}{\partial t} \left(\frac{P_1}{V_1} \right) \quad (27)$$

Finally:

$$\frac{\partial V_1}{\partial t} = \underbrace{-\rho v_1 P_1}_{\alpha} \frac{1}{V_1} - \underbrace{2\rho v_1 \hat{I}}_{\beta} - \underbrace{(\rho v_1 P_1 t - \rho X_{1,0} P_1)}_{\gamma} \frac{1}{V_1^2} \frac{\partial V_1}{\partial t} \quad (28)$$

This same derivation can be repeated for any other position of the node n between 1 and N , giving a differential equation of the form:

$$\frac{\partial}{\partial t} V_n = \alpha \frac{1}{V_n} + \beta - (\alpha t + \gamma) \frac{1}{V_n^2} \frac{\partial V_n}{\partial t} \quad (29)$$

For which the general solution for any n is

$$V_n(t) = \left(-\frac{\gamma_n}{2V_{n,0}} + \frac{V_{n,0}}{2} + \frac{\beta_n t}{2} + \sqrt{4(\alpha_n t + \gamma_n) + \left(\frac{\gamma_n - V_{n,0}(\beta_n t + V_{n,0})}{V_{n,0}} \right)^2} \right) \quad (30)$$

Where the terms α_n , β_n , and γ_n are given by:

$$\alpha_n = -\rho \left(\sum_{k=1}^n v_k \right) \cdot P_n \quad (31)$$

$$\beta_n = -\rho \hat{I} \left(\sum_{k=1}^n (N-k) v_k \right) \quad (32)$$

$$\gamma_n = -\rho \left(\sum_{k=1}^n X_{k,0} \right) \cdot P_n \quad (33)$$

Yet a more interesting insight is offered by the derivative of V_n with respect to time:

$$\frac{\partial V_n}{\partial t} = \frac{\beta_n}{2} + \frac{\partial}{\partial t} \left(\frac{\sqrt{4(\alpha_n t + \gamma_n) + \left(\frac{\gamma_n - V_{n,0}(\beta_n t + V_{n,0})}{V_{n,0}} \right)^2}}{2} \right) \quad (34)$$

system in the study as the values of line resistance per unit length are at the order of $\theta(10^{-4})$ (in SI units), the line current at, or higher than, $\theta(10^2)$, the vehicle velocity at the order of $\theta(10^1)$, the section lengths at the order of $\theta(10^3)$, and the power at the order of $\theta(10^2)$ or even higher [1, 2]. Consequently, $\theta(\alpha_n) = \theta(10^2)$, $\theta(\beta_n) = \theta(10^0)$, and $\theta(\gamma_n) = \theta(10^4)$ or $\theta(10^3)$ depending on n . The important consequence is that the derivative can be thereby simplified to:

$$\frac{\partial V_n}{\partial t} \approx \frac{\beta_n}{2} + \frac{4\alpha_n - 2\beta_n \left(\frac{\gamma_n - V_{n,0}}{V_{n,0}} \right)}{4\sqrt{4\gamma_n + \left(\frac{\gamma_n - V_{n,0}}{V_{n,0}} \right)^2}} \quad (36)$$

Where the denominator can be simplified to allow writing

$$\frac{\partial V_n}{\partial t} = \frac{\beta_n}{2} + \frac{4\alpha_n - 2\beta_n \left(\frac{\gamma_n - V_{n,0}}{V_{n,0}} \right)}{4\sqrt{\left(\frac{\gamma_n + V_{n,0}^2}{V_{n,0}} \right)^2}} \quad (37)$$

Leading to

$$\frac{\partial V_n}{\partial t} = \frac{1}{2} \beta_n \left(1 - \frac{\gamma_n - V_{n,0}^2}{\gamma_n + V_{n,0}^2} \right) + \frac{\alpha_n V_{n,0}}{\gamma_n + V_{n,0}^2} \quad (38)$$

Or ultimately to:

$$\frac{\partial V_n}{\partial t} = \frac{\beta_n V_{n,0}^2 + \alpha_n V_{n,0}}{\gamma_n + V_{n,0}^2} = \text{constant!} \quad (39)$$

The benefit of this equation is that it offers a constant value benchmark for the rate of change in voltage over a short period of time at the node of interest n , allowing to re-write the partial differential as a constant slope equation:

$$\frac{\Delta V_n}{\Delta t} = \frac{\beta_n V_{n,0}^2 + \alpha_n V_{n,0}}{\gamma_n + V_{n,0}^2} \quad (\text{for } \Delta t \leq 10s) \quad (40)$$

B. A comment on the computation of γ_n

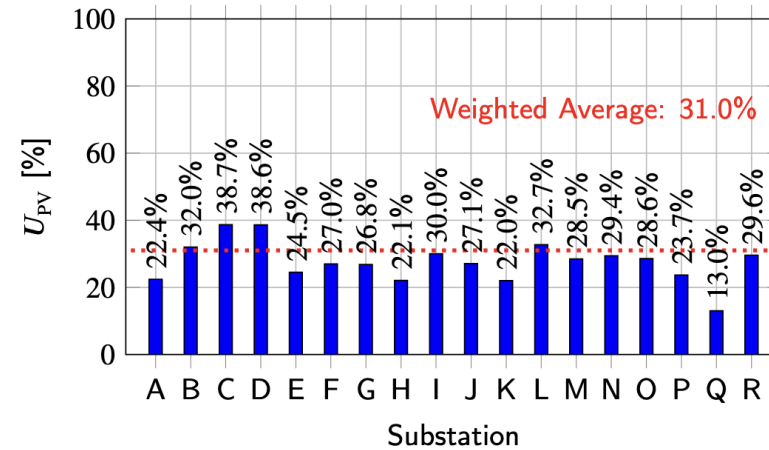
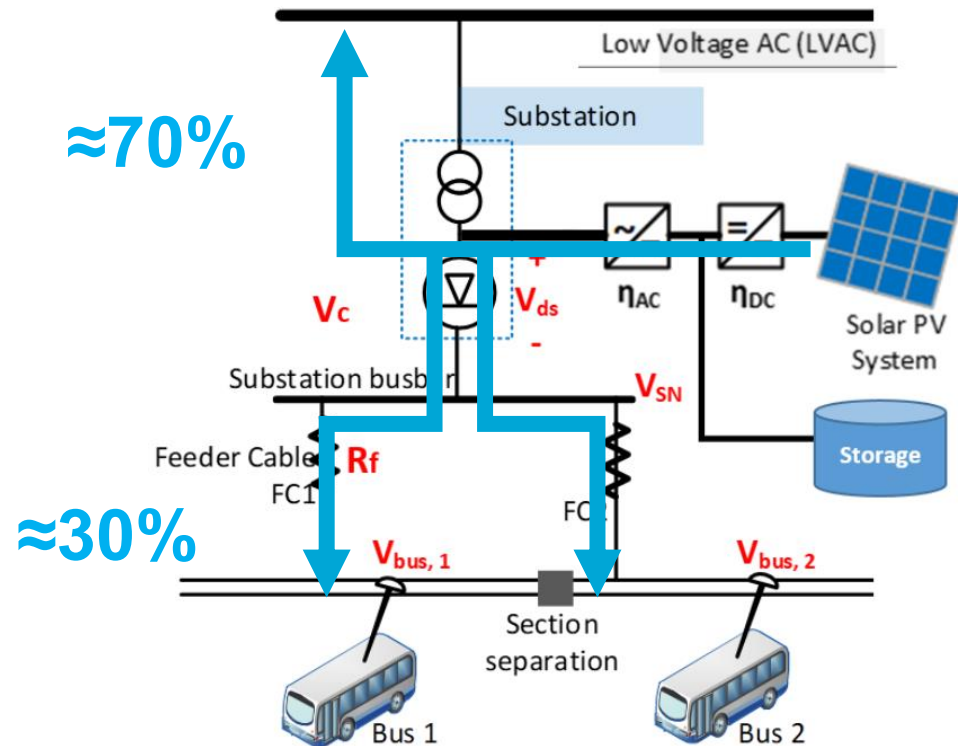
A concern that can be raised is that the parameter γ_n requires knowledge of the original positions of the other load nodes on the section. While this information is not known, it is still reassuring that the sensitivity of the multi-variable Eq.40 with respect to the variable γ_n , given by

$$\frac{\partial}{\partial \gamma_n} \frac{\Delta V_n}{\Delta t} = -\frac{\beta_n V_{n,0}^2 + \alpha_n V_{n,0}}{(\gamma_n + V_{n,0}^2)^2} \quad (41)$$

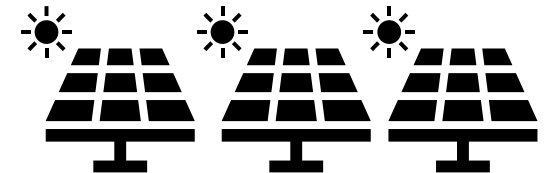
is at the order of $\theta(10^{-5})$. Consequently, the propagation of error from the $\sum_{k=1}^n X_{k,0}$ term, whose elements are the order of $\theta(10^3)$, into Eq. 40, is at the order of $\theta(10^{-2})$ or $\theta(10^{-1})$. Fortunately, the error in assuming the original position of the other nodes $\forall k \neq n$ can be easily compensated for. One

PART II

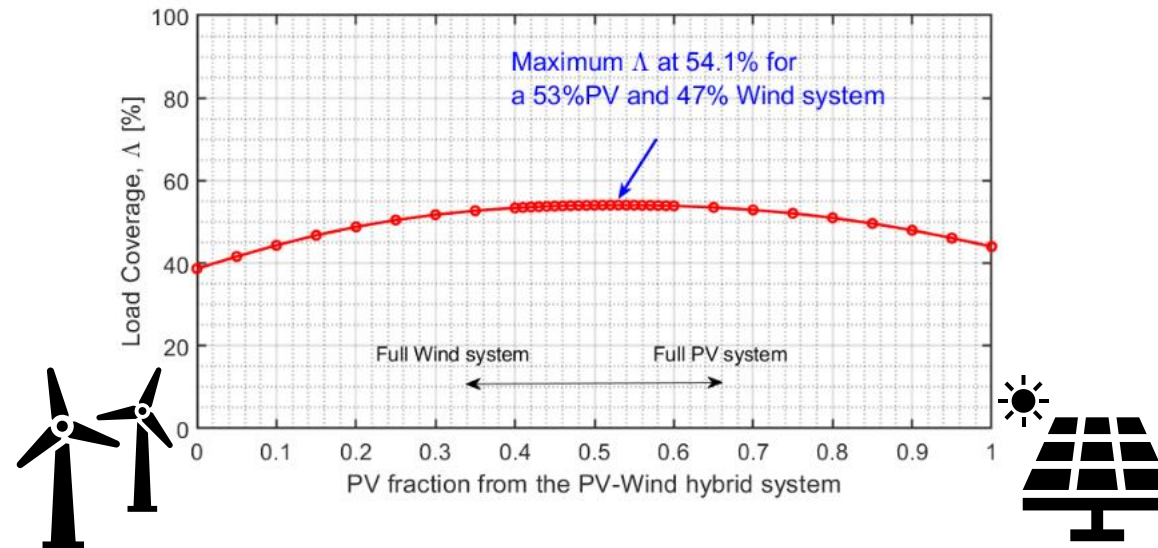
Renewables in Trolleygrids: PV Systems



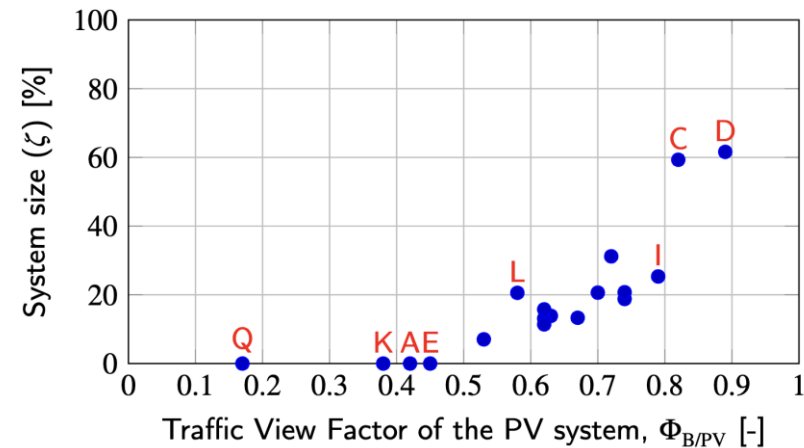
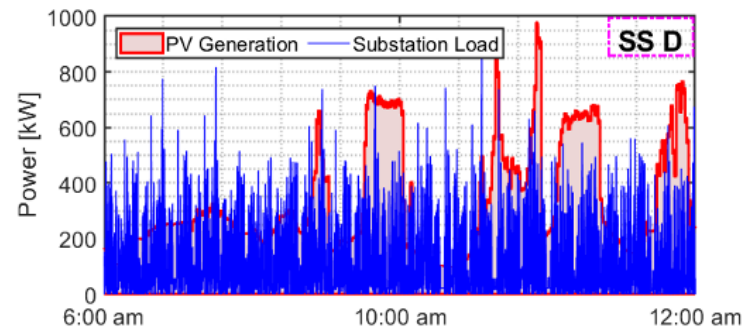
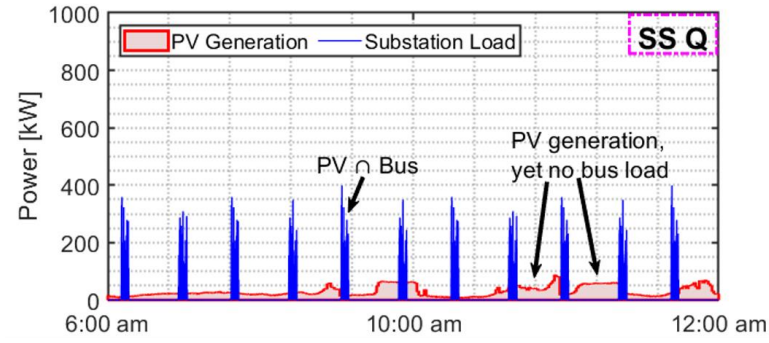
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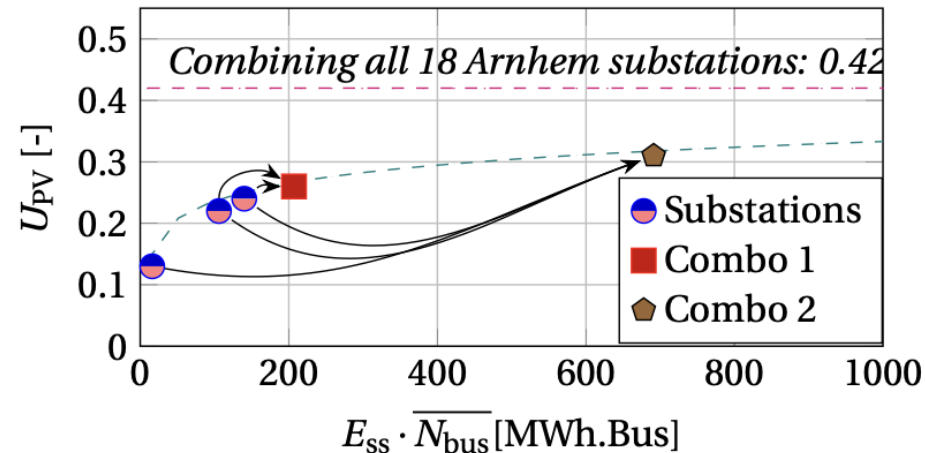
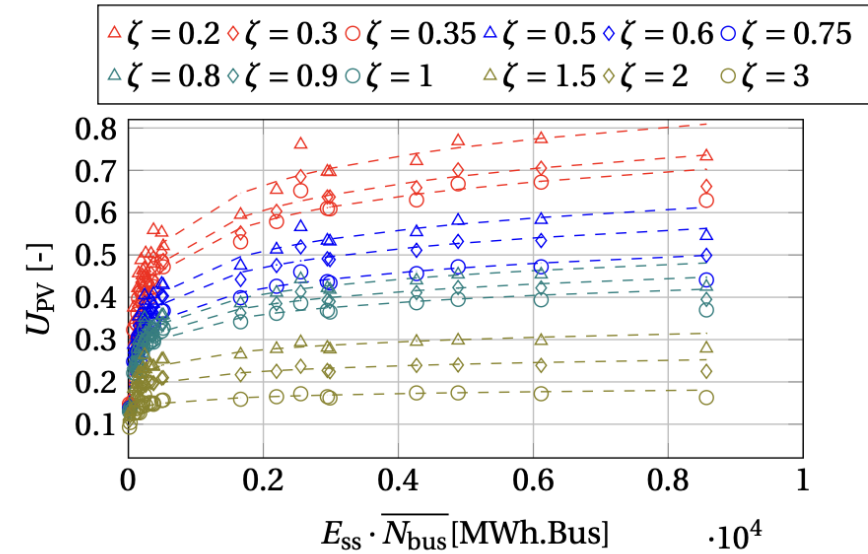
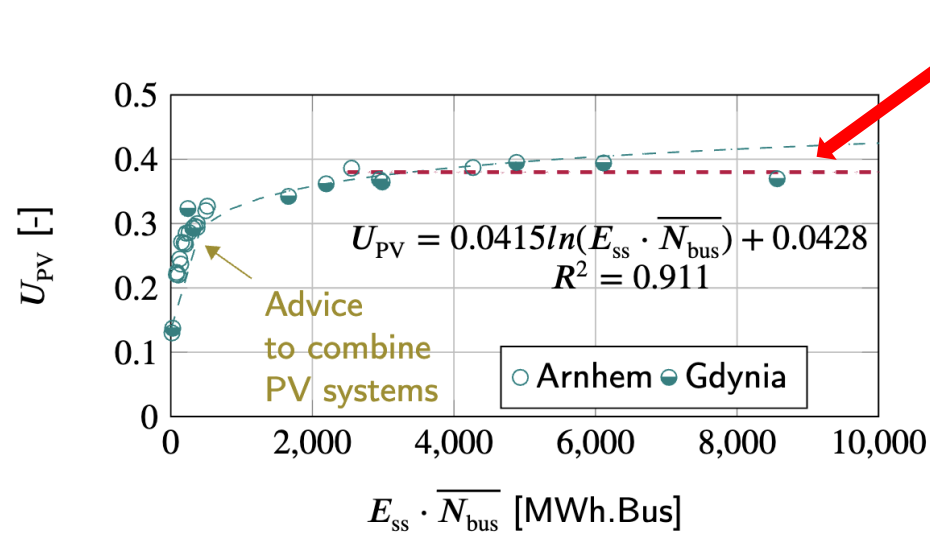
Renewables in Trolleygrids: PV and Wind



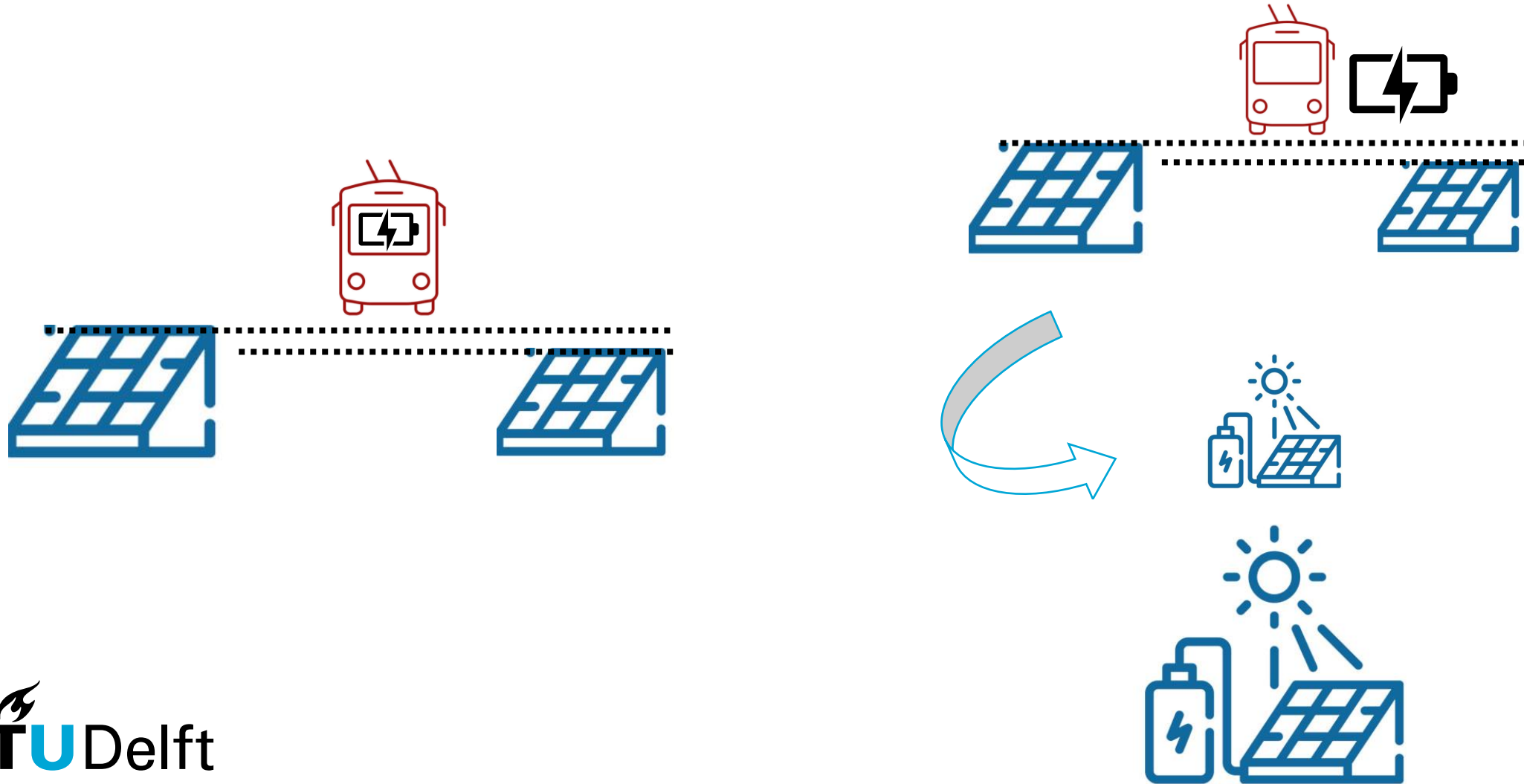
Renewables in Trolleygrids: An Inherent Problem



Estimating PV System Performance in Trolleygrids

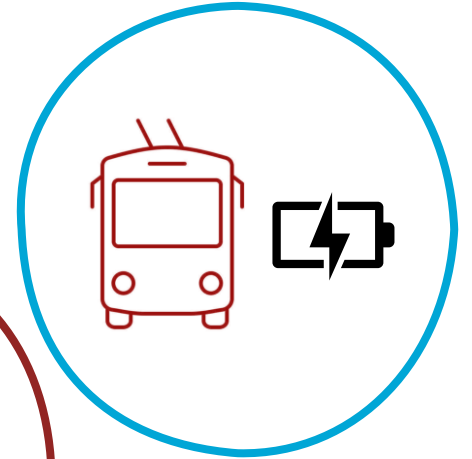
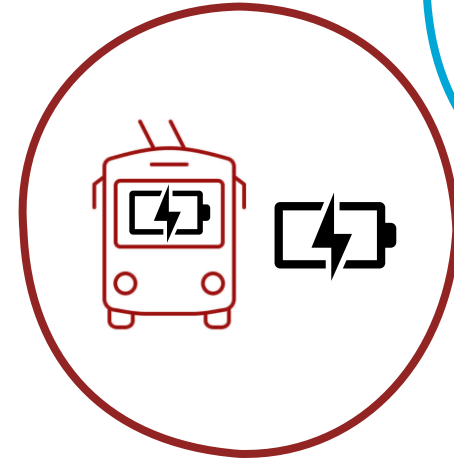


Comparison of Energy Storage for PV in Trolleygrids

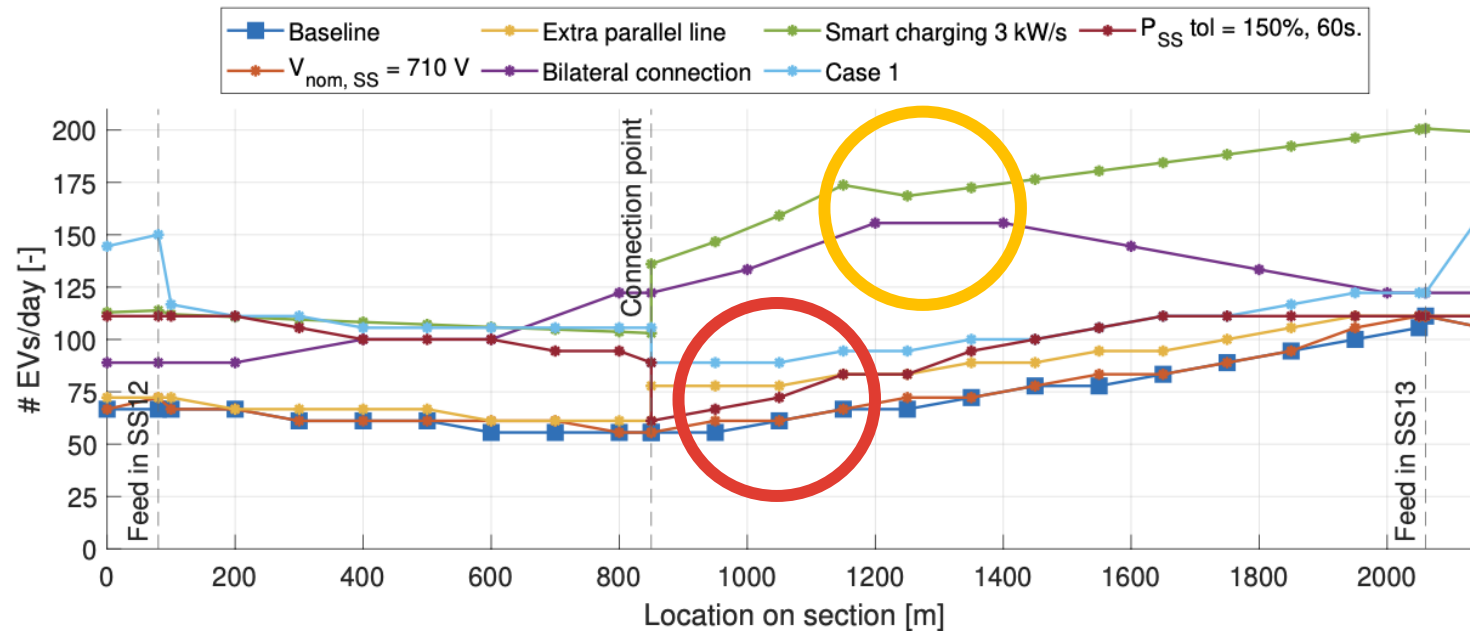


PART III

Storage as a "Base" Load



Electric Vehicle (EV) Chargers as a "Base" Load



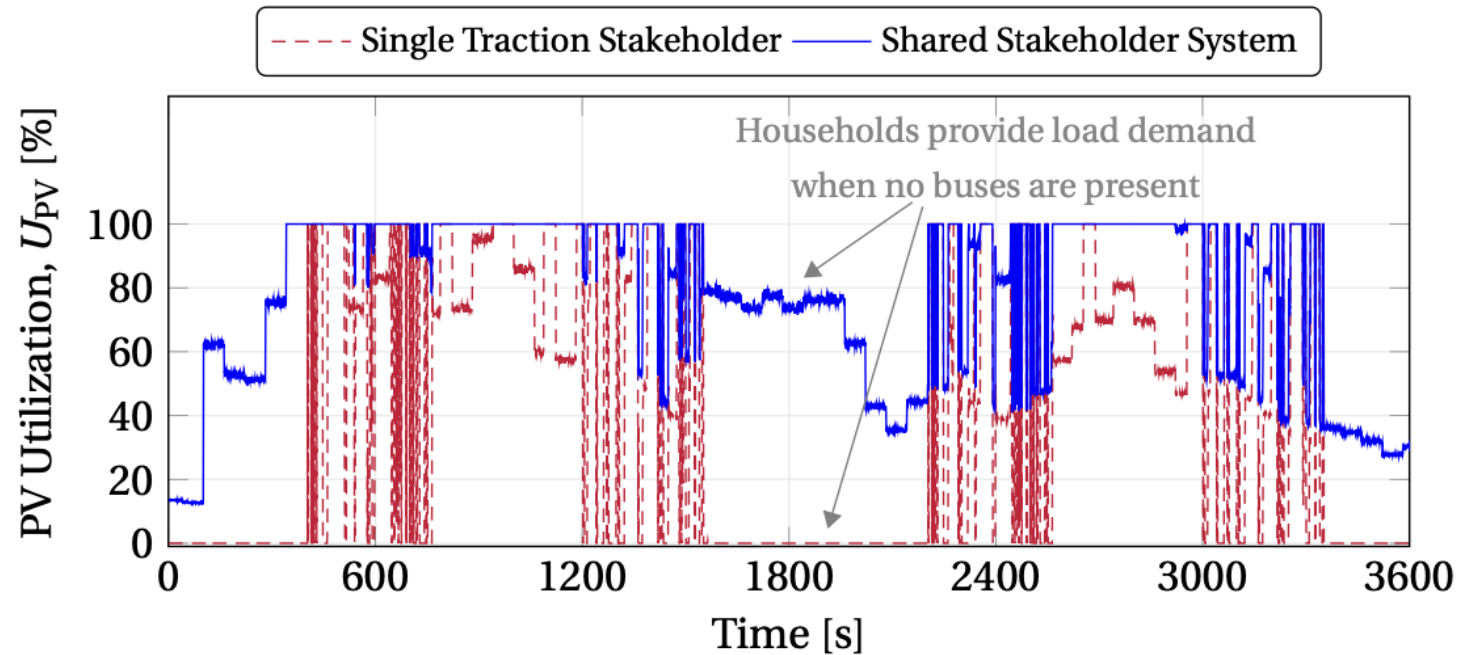
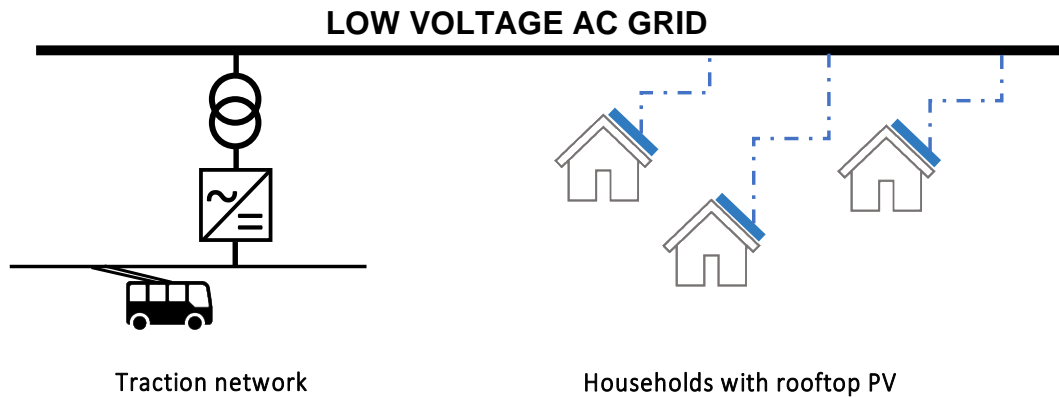
UP TO 200/day



Applications

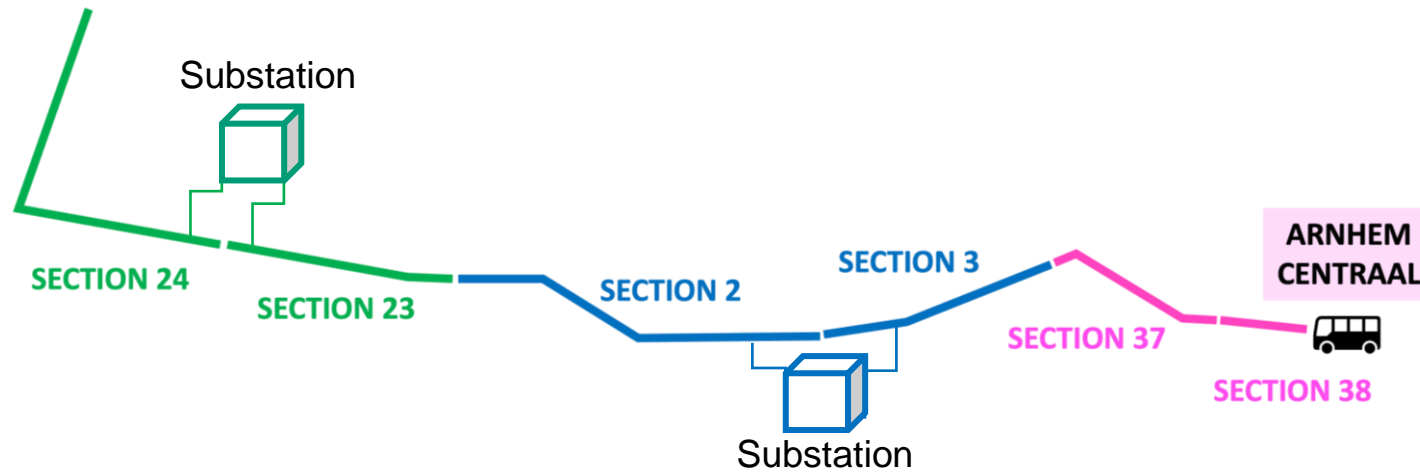
- EV Charger Parks
- Modular EV Fast Chargers
- Industrial Battery Chargers
- Industrial Current Source

Residential Loads as a "Base" Load



PART IV

Conventional IMC Charging



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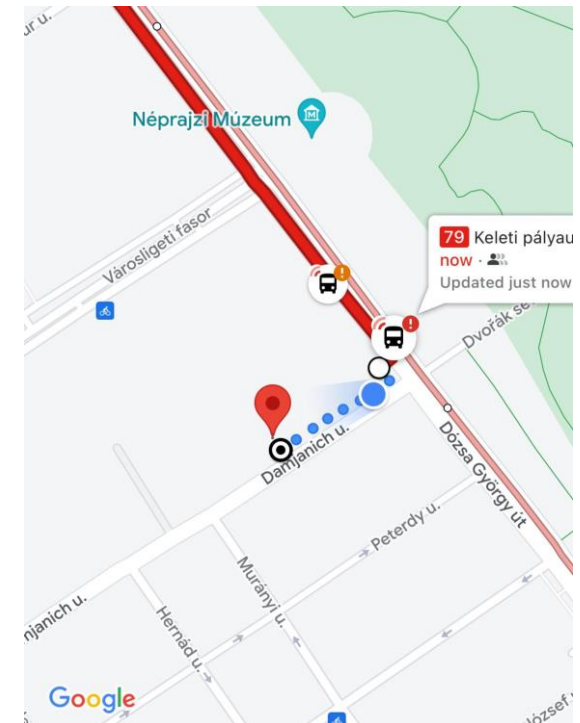
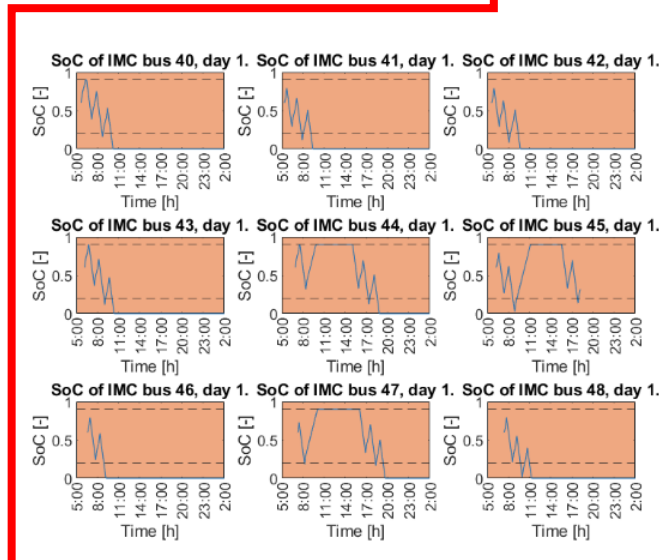
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IMC Charging Schemes: Adaptive Charging

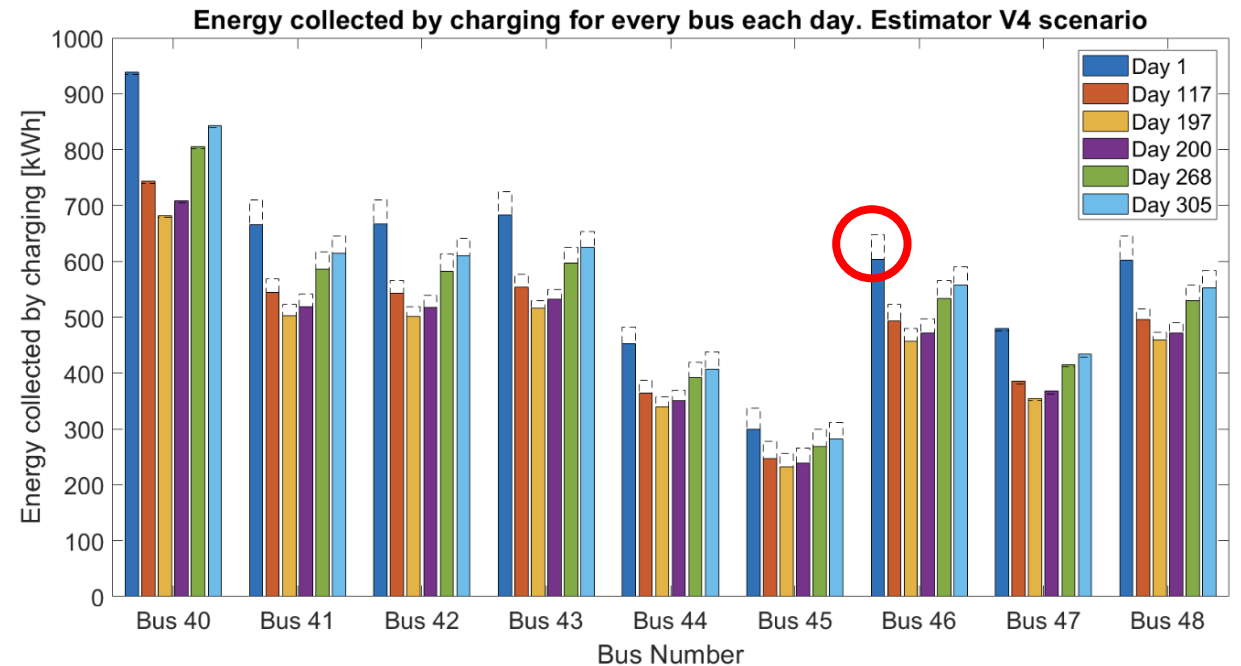
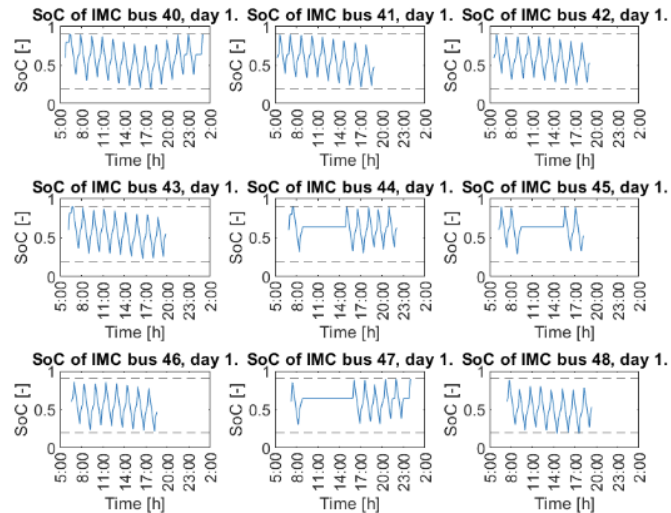
ADAPTIVE CHARGING

| | | Line 4 | Line 13 | Line 29 | Line 352 |
|--|--------------------------------|-------------|-------------|-------------|-------------|
| Adaptive Charging ([Π standing; Ψ moving]) | SS1 | | | | No Charging |
| | SS2 | | [200;300kW] | [200;300kW] | |
| | SS3 | | | No Charging | |
| | SS4 | [100;150kW] | [100;150kW] | [100;150kW] | [100;150kW] |
| | SS5 | | | [100;150kW] | |
| | SS9 | [200;500kW] | | | |
| | SS10 | | | [200;300kW] | |
| | SS12 | | | | No Charging |
| Regular Charging ([Π standing; Ψ moving]) | For any SS on the route | [100;150kW] | [100;150kW] | No Charging | No Charging |

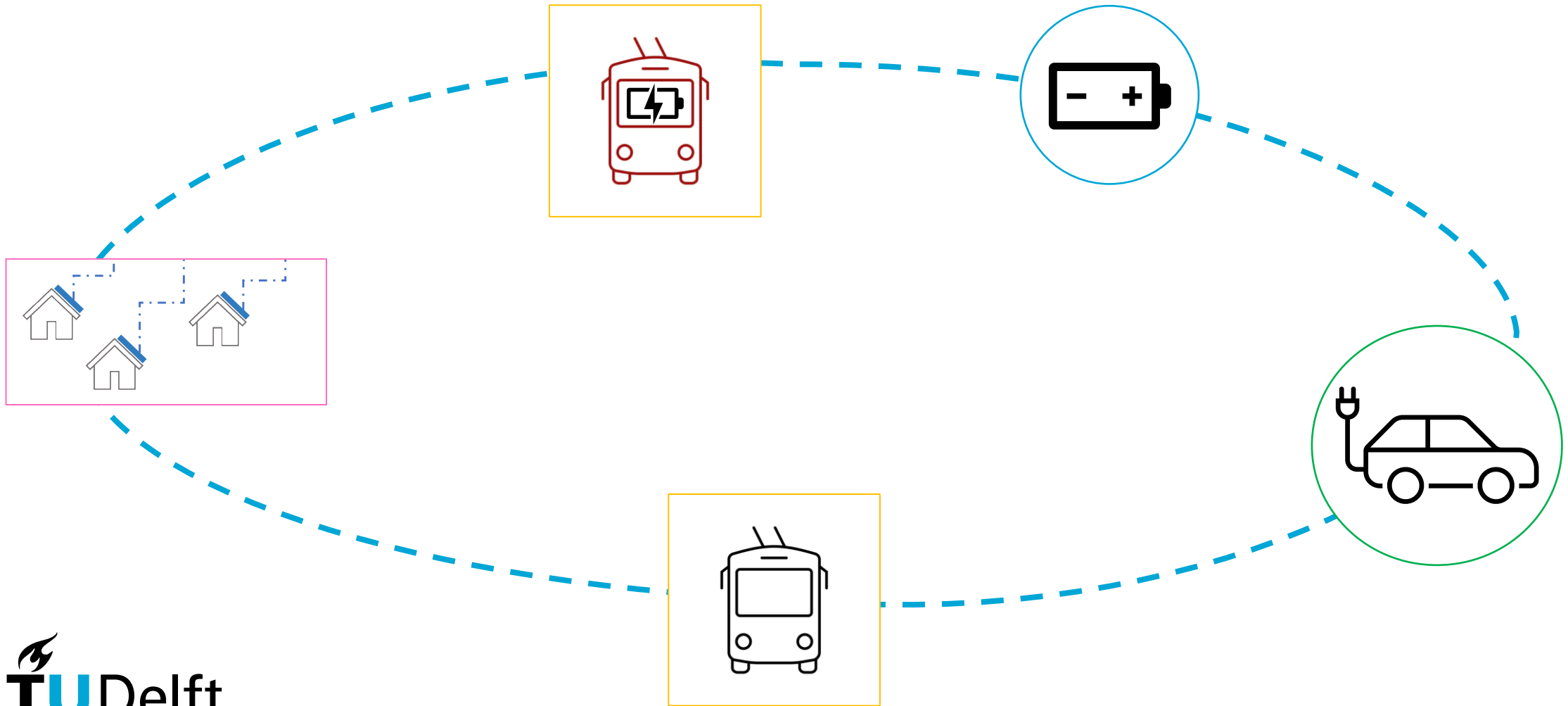


IMC Charging Schemes: Valley Charging

VALLEY CHARGING



Ch12: The Trolleygrid of the Future



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AS SUSTAINABLE, MULTI-FUNCTIONAL,
AND MULTI-STAKEHOLDER
ELECTRICAL INFRASTRUCTURES

Thinking outside of the bus

Thank You!

