Smart Integration of Wireless Electric Vehicle Charging Infrastructure for Provision of Grid Flexibility Services

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Motivation

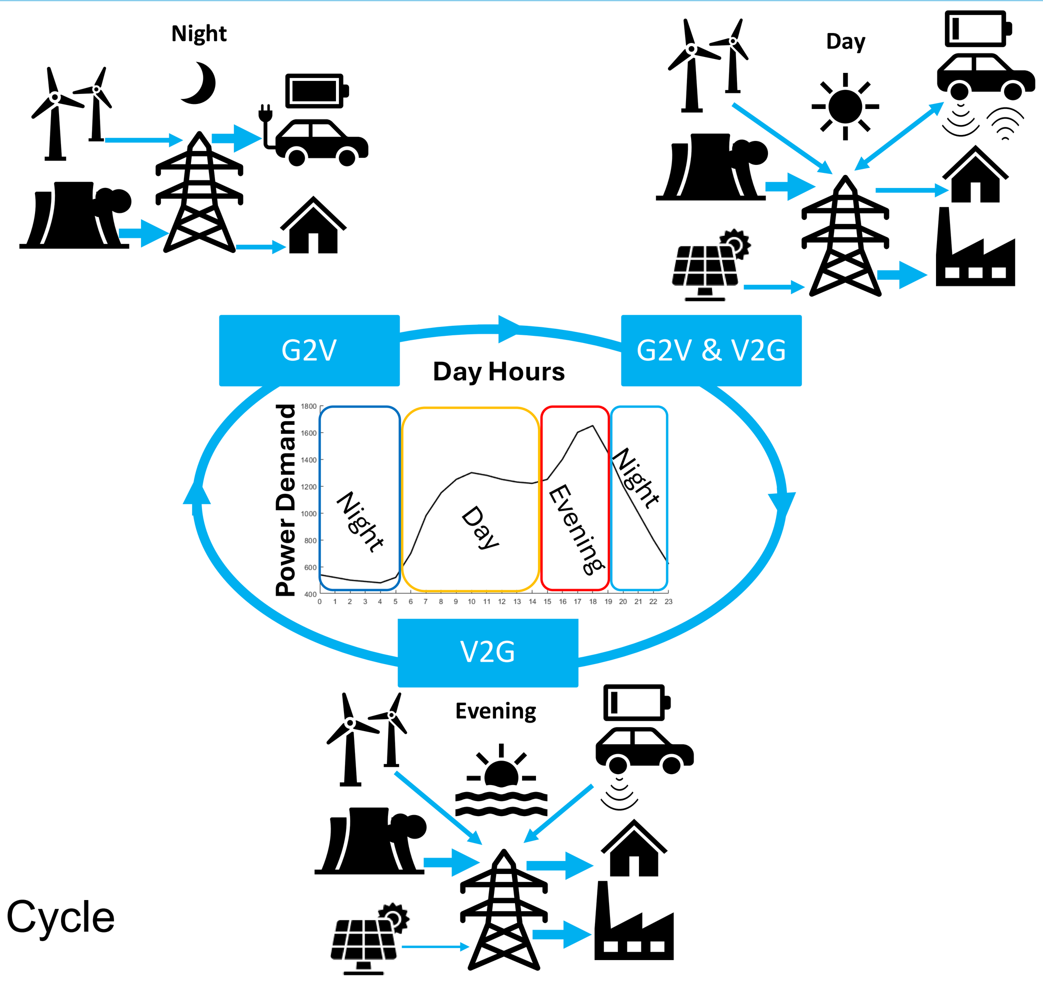
Global context: EV Adoption and Grid Challenges

Challenge: EV adoption is hindered by grid stress, charging delays and range anxiety

Dynamic Wireless Power Transfer (DWPT) enables in-motion charging → reduces range anxiety & stationary charging peaks

Integration with V2G + RES allows demand shaping, regulation, and CO_2 reduction

Goal:
- Optimal DWPT placement in city's road network
- Scheduling for V2G and G2V services
- Assess grid impact (voltage/frequency stability)
- Evaluate RES utilization, CO_2 emission reduction, and economic feasibility



Energy Cycle

Study Area & EV Fleet

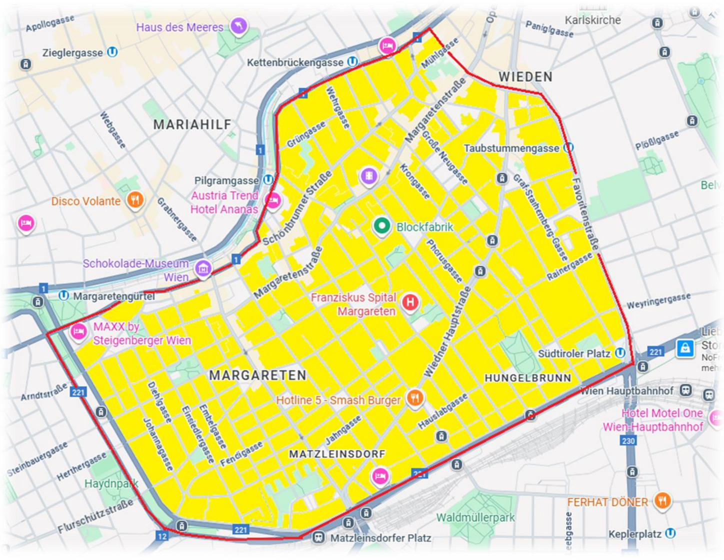
City: Vienna
Area: Approximately **7 km²** (**437** road pads, **220** nodes)

EV fleet composition:
80 × Tesla Model 3 LR (78 kWh battery, ~15–20 kWh/100km consumption)
120 × Renault ZOE (52 kWh battery, 15–20 kWh/100km consumption)

Energy price: Approximately €0.3/kWh

DWPT capability: ±11 kW (compatible with SAE J2954 WPT3)

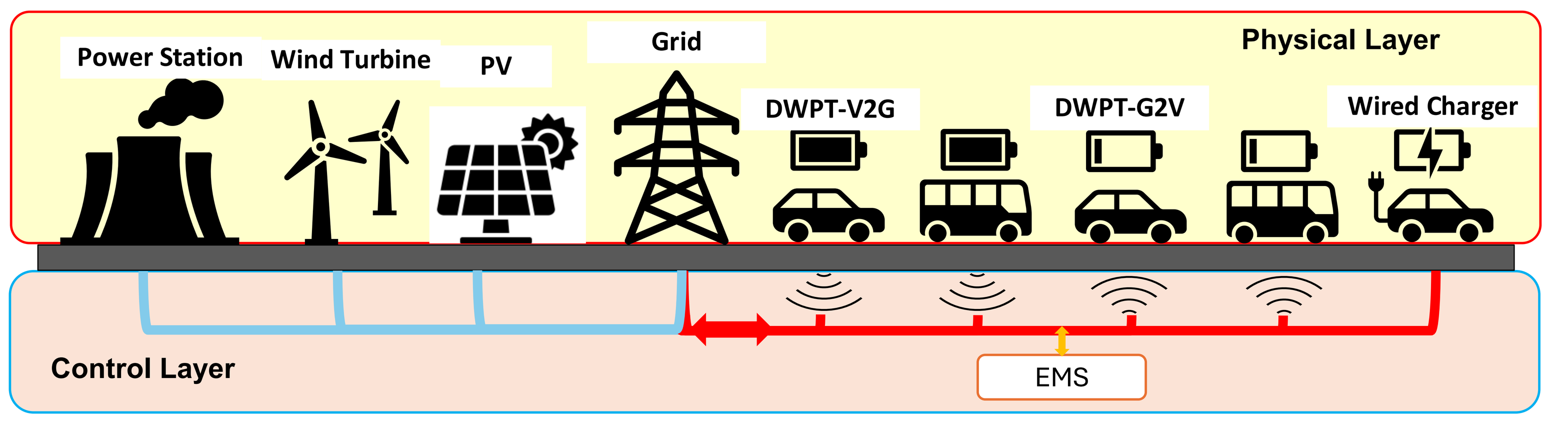
DWPT



Map of investigated area in Vienna

System Architecture

Layers diagram:
- **Physical Layer:** EVs, DWPT pads, wired charging, RES (solar, wind), Conventional generators, Grid
- **Control Layer:** Energy Management System (EMS), Predictive optimization, V2G coordination **Stage I (placement) + Stage II (scheduling)**
- **Service Layer:** Grid flexibility (frequency, load balancing), CO_2 emission reduction



System architecture illustrating

Optimization Stage I : WPT Placement

Variables:
$x_{ij}^{k} \in \{0,1\}$: 1 if WPT type k installed on road segment (i, j), 0 otherwise
d_{ij} : Length of road segment (i, j) [km]
α_k : Cost factor for installing DWPT type k [€/km]
$P_k(t)$: Power demand of DWPT type k at time t [kW]

Constraints:
- Minimum coverage requirement

$$\sum_{k,(i,j)} x_{ij}^{k} \geq 1$$

- Ensure each segment provides at least E_{min} *energy* to passing EVs over the time horizon

$$\sum_{t,k,(i,j)} x_{ij}^{k} P_k(t)\Delta t \;\geq\; E_{\min}$$

Objective: Minimize total placement cost

$$\min \;\; C_{placement} = \sum_{k,(i,j)} \alpha_k \, d_{ij} x_{ij}^{k}$$

Scenarios:
S1: Optimal DWPT placement (budget-constrained)
S2: DWPT only on arterials (main)
S3: DWPT on all roads (no budget limit)
S4: Wired chargers only

Stage II : Dynamic V2G and G2V Scheduling

Variables:
$P_n(t)$: Power of EV n at time t [kW] (+ for V2G and – for G2V)
$SOC_n(t)$: State of charge of EV n at time t [kWh]
Cap_n :Battery capacity of EV n [kWh](52 or 78)
$y_n(t) \in \{0,1\}$: 1 if EV n is connected to WPT at time t, 0 otherwise

SOC Dynamics:

$$SOC_n(t+\Delta t) = SOC_n(t) + \frac{\eta P_n(t)\Delta t}{Cap_n} - \frac{\varphi_n}{Cap_n} d_{ij}(t)$$

Where:
- η charging/discharging efficiency
- ϕ energy consumption per km for EV n [kWh/km]

Constraints:

$$SOC_{\min} \leq SOC_n(t) \leq SOC_{\max}$$

$$P_{n,dch} \leq P_n(t) y_n(t) \leq P_{n,ch}$$

Objective:

$$\min(C_{op} + C_{ch/dis} - R_{V2G} + \phi \sum_t P_{tot}(t)^2)$$

with

$$P_{tot}(t) = P_{grid}(t) + \sum_n P_n(t)$$

C_{op}= cost of operation, $C_{ch/dis}$= cost of charging/discharging R_{V2G}= revenue of V2G service, $\phi \sum P_{tot}(t)2$ = penalty for large deviations in total active power

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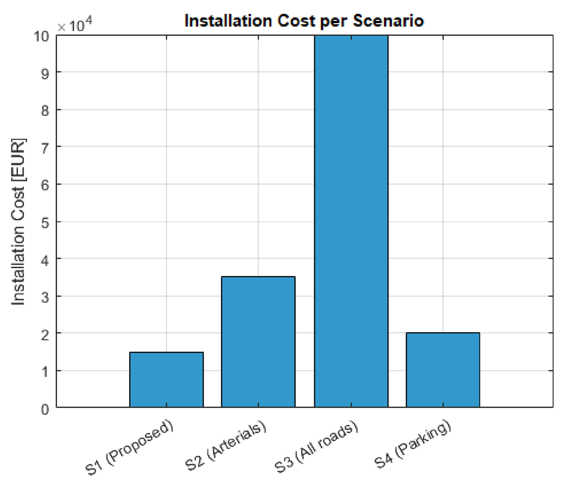
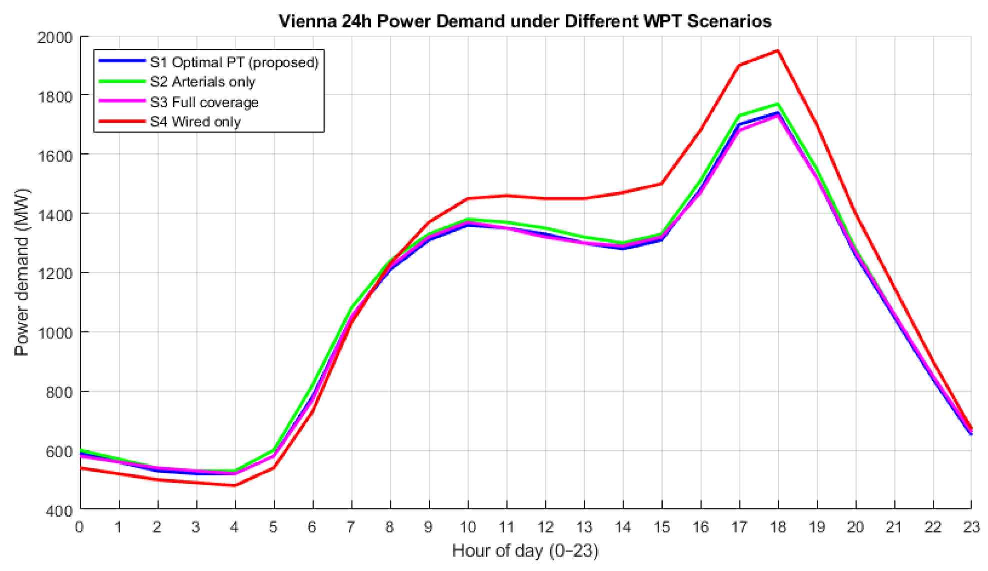
Stage I : Simulation Results

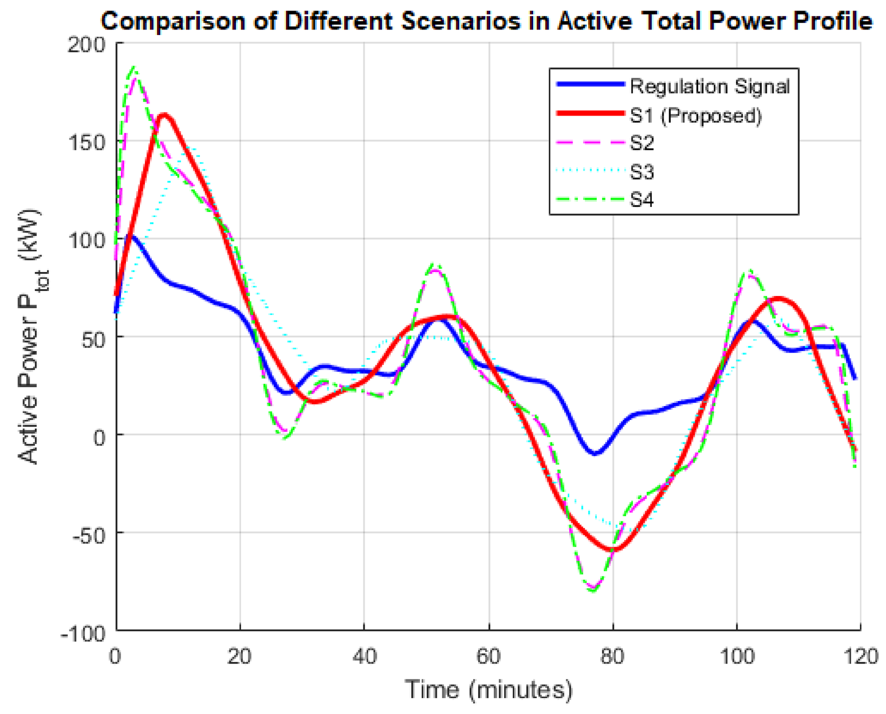
Simulates 24-hour electricity demand for Vienna
Shows daily peaks and low-demand periods
Different scenarios illustrate the impact of varying consumption patterns
Enables comparison of costs under different demand scenarios
Supports efficient planning and city-scale energy management

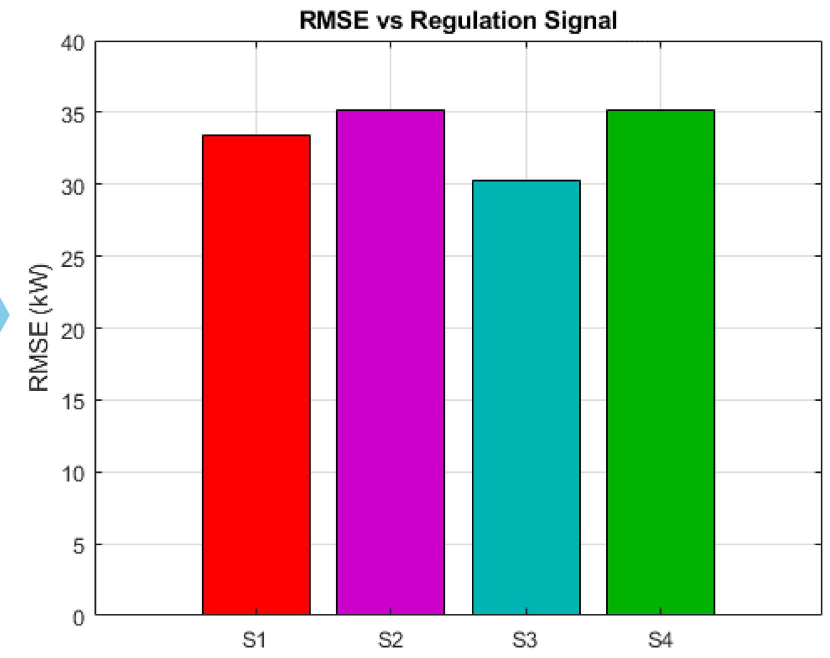




Stage II : Simulation Results

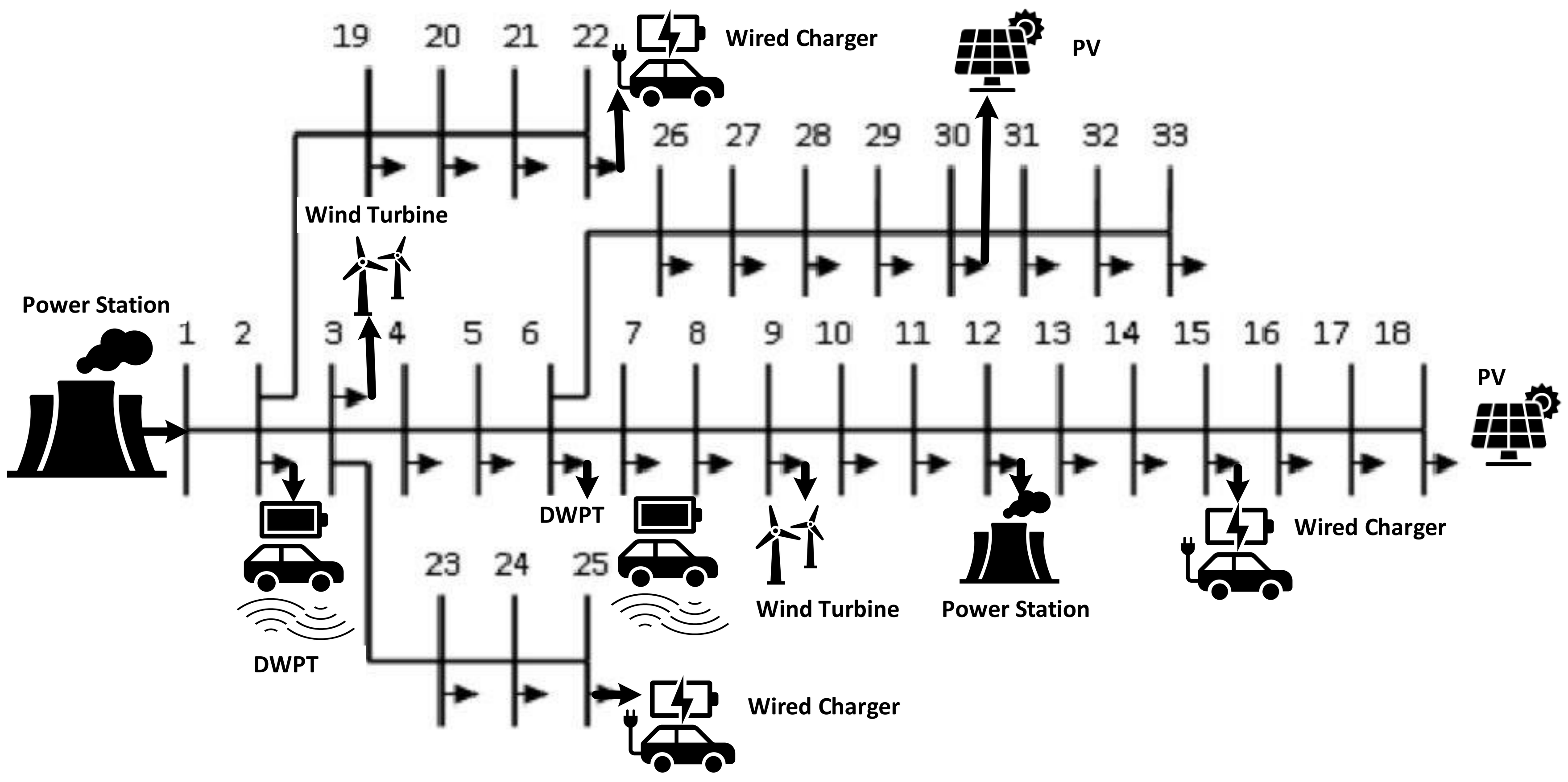
Horizon: 8:00–10:00 AM, Δt=1 min
Fleet: 200 EV (Model 3+ZOE)
Charging, discharging limit: ±11 kW
Efficiency: η = 0.9
Regulation signal: The mismatch between generation and demand
S1 attempts to tracks it



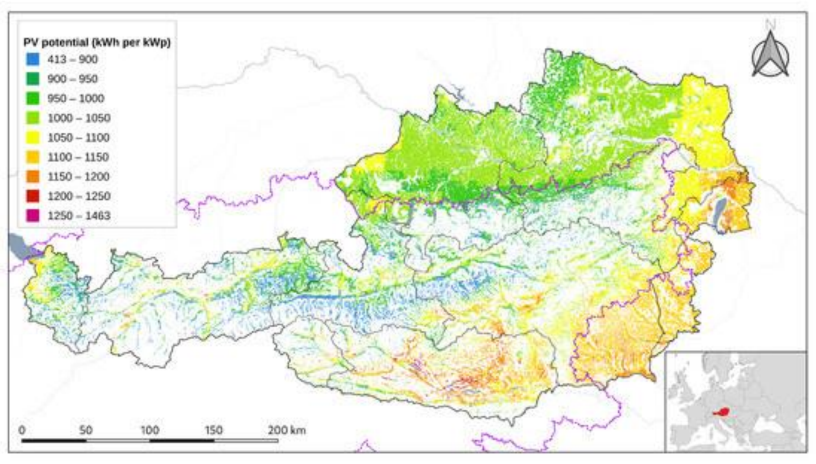


Power Distribution Grid Impact Analysis

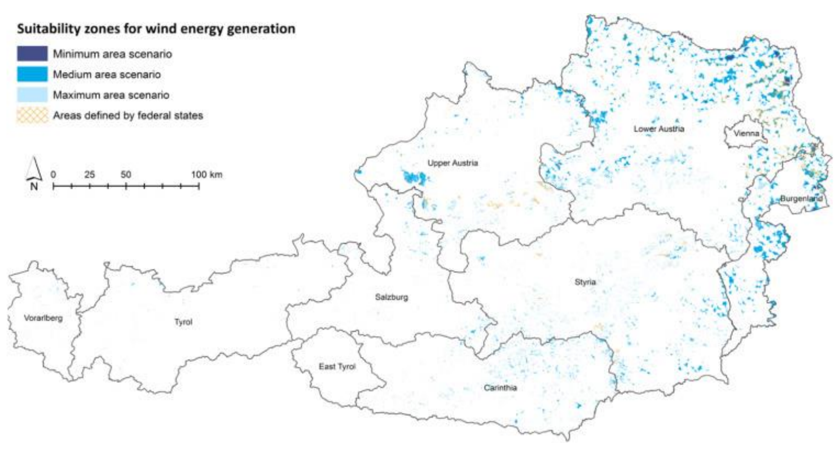
Approach:
Use **IEEE-33 bus system**
Inject DWPT roadway loads at Bus-2 (near source) and Bus-6 (weak bus)
Traffic flow: Monte Carlo method using historical Vienna traffic
RES data: Wind + PV generation profiles from Vienna region
Compare S1 to S4 Scenarios at ±11 kW per segment



The enhanced IEEE 33 bus distribution test system



Austrian ground–mounted PV potential

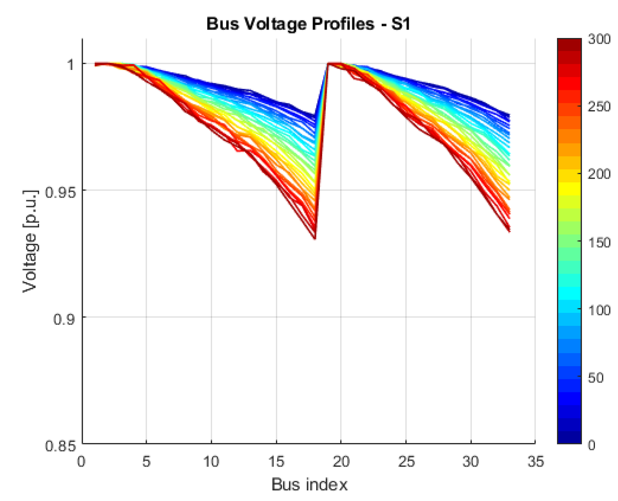


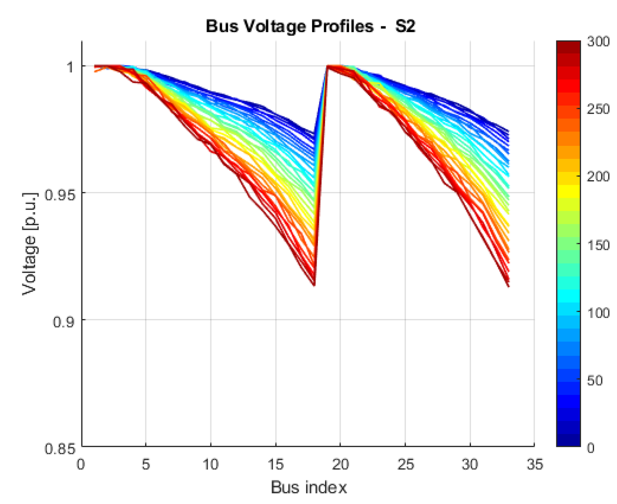
Austrian wind energy potential

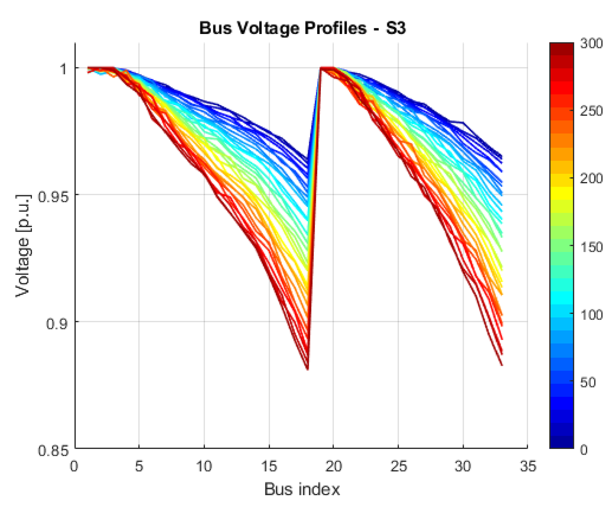
Simulation Results

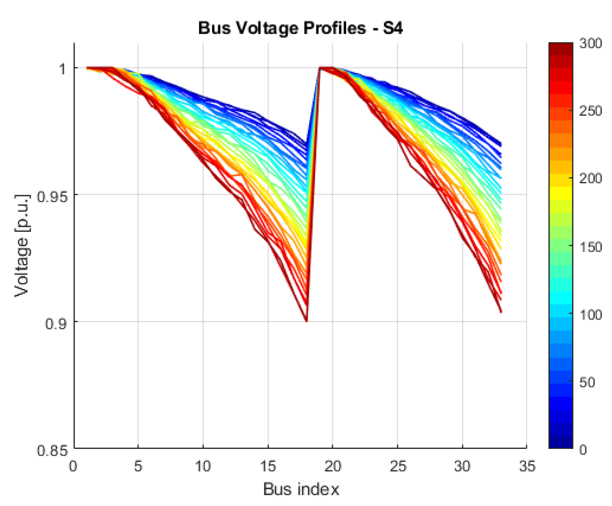
S1 maintains good stability (min ~0.92 p.u.), safely above the standard
S2 (~0.91 p.u.) remains within limits but less effective than S1
S3 suffers the largest drop (~0.88 p.u.), stressing the grid
S4 (~0.90 p.u.) operates right at the minimum standard, limited support capacity

With the inclusion of RES, local bus voltages are further stabilized by considering their scheduling, including weather conditions and adjustments









Conclusion

- Optimal DWPT placement and dynamic V2G and G2V scheduling reduce grid power fluctuations and track regulation signals
- Bus voltage profiles confirm stability, and scheduled PV and wind generation further enhance local voltages
- S1 provides the good balance of technical performance, grid support, and cost efficiency across all scenarios

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