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# Evaluating the Impact of Grid Connected Solar-Hybrid Trucks

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Master's Programme in Renewable Electricity Production

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## Abstract

As the electrification of heavy-duty transportation grows, a collaborative project is working to develop a solar-equipped trailer for a plug-in solar hybrid truck. The integration of the hybrid truck with the grid presents new opportunities and challenges. Since the solar hybrid trucks have the capability to produce electricity through their photovoltaic (PV) panels, the impact of PV integration into the grid across all four seasons of the year is being observed.

The potential impact of hybrid trucks during idle periods will be studied as the trucks can be recognized as distributed energy resources. The thesis project focuses on three study cases. The first involves hybrid trucks injecting the power produced by the truck PVs into the distribution grid when their batteries are full. The second case simulates where the power produced by the truck PVs is used to charge their own batteries. The third case assesses the hosting capacity to determine the maximum number of trucks that can be integrated into the grid without violating the grid performance threshold.

The simulation is performed in Simulink to estimate the PV production of the trucks and evaluate integration of hybrid trucks fleet into the grid. The simulation model is designed to allow the scalability of the truck fleet. The models can also determine how an increasing number of hybrid trucks affects critical grid parameters, particularly voltage and frequency. These two parameters are the most important to observe regarding grid quality. The results show that while a fleet of 80 hybrid trucks contribute a significant amount of power to the grid, the grid voltage and frequency remain within standard limits.



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# 1. Introduction

Mitigating climate change needs global efforts to reduce greenhouse gas (GHG) emissions and achieve clean energy transition. Reducing emissions from power generations, vehicles, and industries is one of the key actions to address the climate change. Addressing this challenge requires society as a whole to change its behavior, from generating electricity to transporting people and the products they consume [1]. From a global perspective, the average temperature increase can be limited to 1.5°C above pre-industrial levels (1800–1900) by achieving net-zero emissions [2].

The European Union (EU) has already made significant progress, reducing emissions by more than 37% in 2023 compared to 1990 levels. The EU has also set a more ambitious target of a 55% reduction by 2030 [1]. Global society needs to be involved to ensure that all emission reduction targets can be met. Otherwise, all the results achieved regionally will not be able to fully prevent climate change.

Renewable energy sources have become central to global efforts to mitigate climate change, with solar photovoltaic (PV) emerging as one of the most widely adopted options. With production costs decreasing every year, the usage of PV technology is increasing massively. Due to the easy accessibility, simple implementation and noiseless operation, solar PV is the most widely used [3].

PV technology has also evolved over the past few decades. Many improvements have been made in the manufacturing industry, from silicon-based solar cells to the use of nanomaterial technology. More recently, developments in thin-film technologies, bifacial modules, and perovskite materials have further increased the PV applications in terms of efficiency and installation simplicity. Although crystalline silicon dominates the commercial market due to the high performance, the use of nanotechnology may be the future of PV technology [4].

Efforts to mitigate climate change include not only expanding the use of renewable energy sources, but also in the electrification of the transportation sector. The mass production of electric vehicles (EVs) gives the huge impact to reduce GHG emission. In addition to increasing the share of renewable energy in the overall energy mix, the growing number of EVs significantly helps overcome the challenge of climate change [5].

Although solar PV and EV offer benefits to the sustainability and environmental perspective, operational challenges to be solved such as frequency and voltage stability [6]. The intermittency of solar energy source affects the power injection the grid. It also happens in EV sector which by nature have unpredictable behavior. Thus, minimizing GHG emissions in the transportation sector, especially the heavy transportation an ongoing challenge.

An innovative solution to this problem involves integrating the vehicle with PV system, reducing both fuel consumption and dependence on fossil energy sources. While PV systems on vehicles present an innovative solution to power heavy transportation with renewable energy, their potential extends beyond vehicle operation.

Currently, a collaborative project is on developing a solar-equipped trailer for a plug-in hybrid truck. As shown in Figure 1, the trailer is with an 18-meter-long solar panel on its roof and sides with a total area of 140 square meters. The solar panels are expected to annually generate 14,000 kWh [7].


Figure 1. Solar Integrated Truck by Scania *[7]*

The presence of PV systems on the hybrid trucks is expected to reduce the dependence on energy imports from the grid to charge the trucks batteries. In addition, the excess power from PV production is automatically injected back into the grid. Evaluating the impact on injecting excess power into the grid is one of the focuses of this project.

Unresolved issues include determining the actual power delivery potential of solar-hybrid trucks based on real operational data and assessing their impact on grid stability. Furthermore, scaling this concept to include multiple trucks—potentially a fleet of 80 or more—raises questions about the collective impact on grid performance. Addressing these gaps is essential to unlock the full potential of integrating PV-equipped vehicles into the energy grid while ensuring compatibility and scalability.

## 1.1 Project Goals

This thesis project aims to observe and quantify the potential of integrating solar-hybrid trucks into the distribution grid, especially during idle periods on the weekend when the vehicles are not in use and available to interact with the grid. The thesis project will assess the energy generation capacity of the PV systems of the trucks and grid support potential of the truck fleet throughout the year. The specific goals of the project are as follows:

- Estimate the potential energy contribution of 80 solar-hybrid trucks to the distribution grid during idle periods across all four seasons of the year.
- Develop scalable simulation models to evaluate the integration of large fleets of solar-hybrid trucks into the grid, identifying the threshold at which grid parameters (e.g., voltage and frequency) may be compromised.
- Estimate whether the power generated by PV system is sufficient to charge the batteries of hybrid trucks during idle periods across all four seasons of the year.

- Assess the impact on grid performance, with a focus on voltage and frequency variations caused by the truck fleet's interaction with the power system.

## 1.2 Project Delimitations

The project aims to develop a model that evaluates the impact of connecting solar-hybrid trucks to grid voltage and frequency. The study assumes that 80 hybrid trucks will be connected during the 48 hours idle period on the weekend.

The model will evaluate the grid voltage and frequency when the fleet of trucks is fully charged and supplying power to the distribution grid. The model is also expected to simulate conditions in which partially charged truck batteries are charged using power produced by the trucks' PV systems. Since the main objective of the PV installations on the trucks is to reduce operational costs and local emissions [8], the possibility of importing power from the grid to charge the battery units is disregarded.

# 2. Methodology

In this project, the hybrid trucks are modeled as dynamic loads that change over time. This means that the truck models are designed to supply power to the distribution grid over a period of time. The fact that hybrid trucks have battery units forces the project to consider the combination of power produced by the PV and the battery load. This study also assumes that a fleet of 80 hybrid trucks will be connected during the 48 hours idle period on the weekend. Thus, the simulation model can specifically evaluate the impact of exporting net power from the fleet of hybrid trucks to the grid.

Since the connection of the hybrid truck fleet is represented by PV systems and battery loads, the significant technical problems arise from the intermittency characteristics of PV systems. The impact of connected PV systems on the grid includes the variation of the voltage and frequency of the grid [9]. Evaluating the grid voltage and frequency stability using a simulation model in Simulink is the focus of this study.

## 2.1 Study Case

The analysis in this project is conducted across three study case scenarios. Simulations are carried out for all four seasons. For each seasonal simulation, three case studies were executed and analysed, as listed below. For each study case, voltage and frequency analysis are the main focus.

a. Grid connecting of fully charged hybrid trucks

   In this case, the 80 hybrid truck batteries are assumed to be 90%-100% state of charge (SoC). By using this assumption, it is expected that all the power output from PV is injected to the grid. This case leads the hybrid truck model to behave only like solar PV generator.

b. Grid connecting of discharged hybrid truck (50% SoC) without importing power from grid

   The initial SoC of the 80 hybrid truck batteries is assumed to be 50% due to the consumption of the trucks during the operating hours. In this case, the possibility of importing power from the grid to charge the batteries is neglected. Thus, the only source of charging power is the installed PV of the trucks. With the above assumption, it is not expected that the grid voltage drop will happen.

c. Hosting capacity assessment

   Hosting capacity assessment is an evaluation of the maximum generation that can be hosted by the distribution grid without violating the grid constraints [10]. In this project, the hosting capacity assessment refers to the worst cases of connecting hybrid trucks as PV generators (case A). In this cases, it is the maximum number of hybrid trucks that can be connected to the distribution grid without compromising its quality.

## 2.2 Solar-Hybrid Truck Model

Simulink is a MATLAB-based block diagram environment which used to design systems. With a graphical block diagram as its primary interface, Simulink is an alternative option to build a model of electrical system. In this project, Simulink is used to model a grid-connected fleet of hybrid trucks based on a real vehicle. This environment is also used to scale up the model of the trucks, since the aim of this project is to have a fleet of 80 hybrid trucks. Therefore, the simulation model must be designed to accurately represent real-world conditions. To simulate the study cases in this project, the hybrid truck model is represented by solar PV model and battery model.

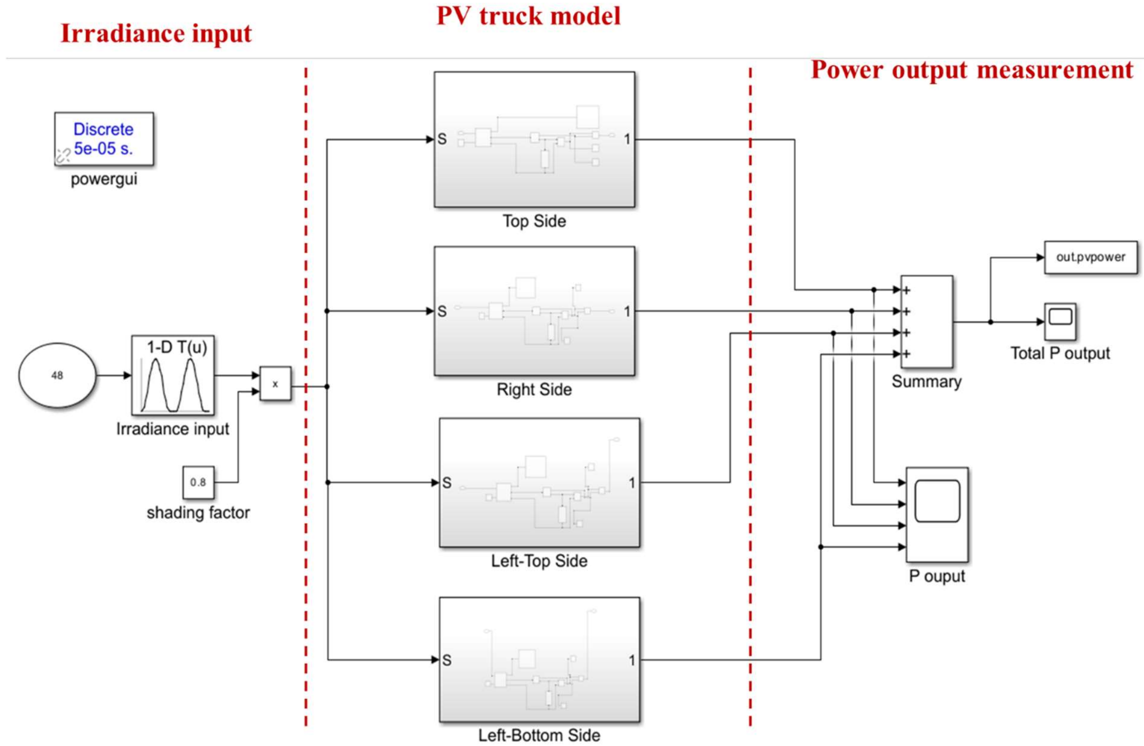
### 2.2.1 Solar PV Model

Each hybrid truck has solar PV panel installed on each side of its trailer: one panel on the top side, one panel on the right side and two panels on the left side. The total power output of the PV systems is 13.7 kWp. Table 1 shows the specifications of PV systems of the hybrid trucks.

Table 1. Specifications of solar PV systems

| Parameter | Location | | | |
|---|---|---|---|---|
| | **Top Side** | **Right Side** | **Left Side-Top** | **Left Side-Bottom** |
| $V_{oc}$ | 420 V | 540 V | 573.75 V | 461.25 V |
| $V_{mpp}$ | 336 V | 432 V | 459 V | 369 V |
| $I_{sc}$ | 7.6 A | 15.2 A | 7.6 A | 7.6 A |
| $I_{mpp}$ | 6.6 A | 13.2 A | 6.6 A | 6.6 A |
| kWp | 2.24 kW | 5.94 kW | 3.06 kW | 2.46 kW |

This project requires the simulation to be run in 48 hours of idle period of hybrid trucks for each seasons. This aims to observe the impact of hybrid trucks when the power produced is injected the grid. The measurement will be focused on the point of common coupling.

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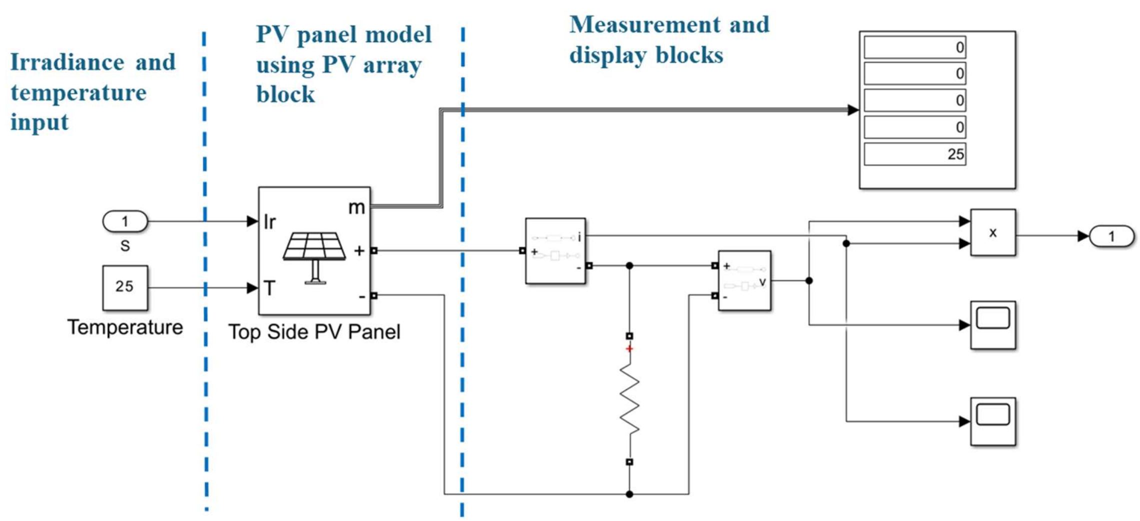
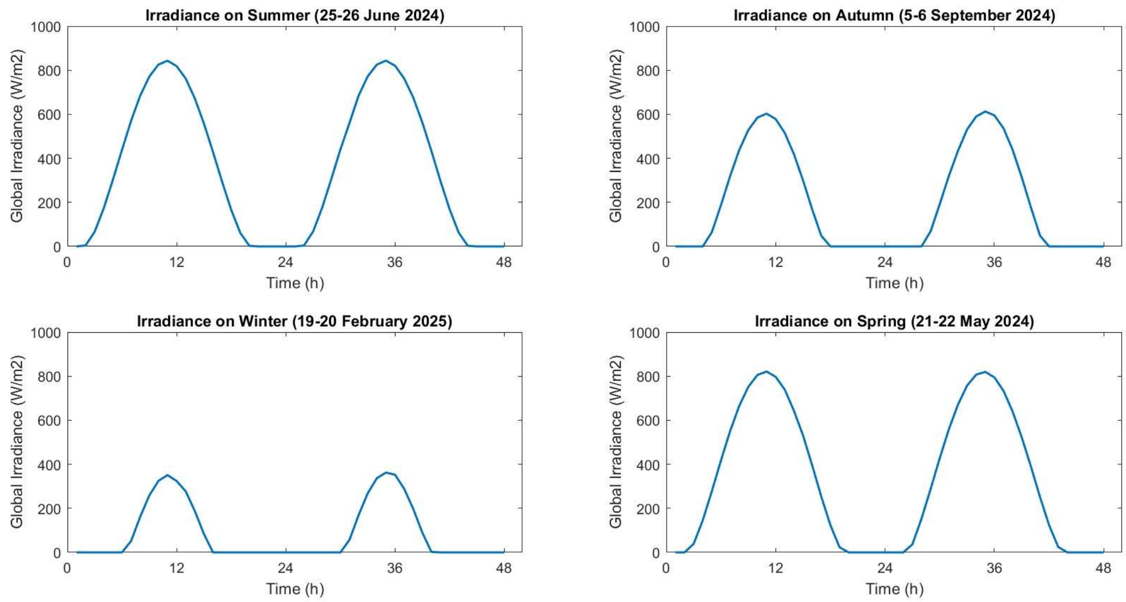



(b)

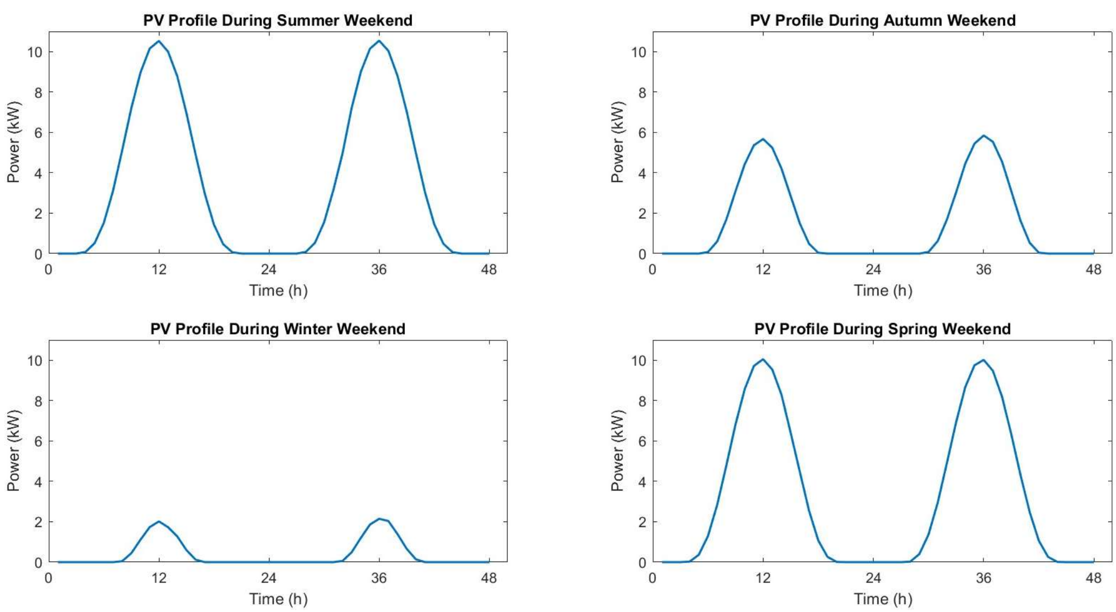
Figure 2. Solar PV generation model in Simulink: (a) PV model for the whole truck trailer; (b) PV model for each side of the truck trailer

Figure 2 shows the solar PV model for a hybrid truck trailer. PV power profile of a hybrid truck is the sum of the power generated by the PV panels on each side of the truck trailer. Figure 2b shows the PV model using PV array block in Simulink. Irradiance and temperature are used as input of PV array block. As shown in Figure 2b, the resistor block is used as the internal resistive load of the PV module. This allows the current output of the PV module to be measured by the current measurement block. With this model, PV profiles can be generated based on specification shown in Table 1.

Irradiance input used the data from the Swedish Meteorological and Hydrological Institute (SMHI) as shown in Figure 3a [11], while the temperature input used standard test conditions in 25°C. Therefore, Figure 3b presents the power profiles generated by the solar PV of a hybrid truck in 4 different seasons. As expected, the highest PV power output occurred during the summer due to the highest irradiation level, followed by spring, autumn, and winter.




(a)




(b)

Figure 3. Irradiance and PV profiles: (a) Irradiance data from SMHI; (b) PV profiles of 1 hybrid-truck

### 2.2.2 Truck Battery Model

Like any other electric vehicles, each solar-hybrid truck which observed in this project also has batteries installed. The total capacity of the batteries is 300 kWh for each hybrid truck [8]. A three-phase dynamic load block is also used to represent the battery in the simulation. The charging behavior of the battery is defined using a charging load profile as the input.

The battery of the trucks are charged using the power from PV production of the trucks to ensure that the vehicles are ready for use during the weekdays. According to best practices, a truck battery is considered fully charged when it reaches 90% SoC to maintain the health and longevity of the battery [12]. The SoC estimation can be calculated with

$$SoC(t) = SoC(t_0) - \frac{1}{E_0(0)} \int_0^t P_i(t)dt,$$

Where $SoC(t_0)$ is the initial SoC, $E_0(0)$ is the initial energy capacity and $P_i(t)$ is the instantaneous export power from battery [13]. In this project, the battery is charged and receives power of the PV, so the value of $P_i(t)$ is always negative.

To simulate the charging case, it is assumed that the maximum charging power is 50 kW for each truck battery unit. This assumption is based on the maximum charging rate using Combined Charging System (CCS) as CCS is the most common charging standard in europe for electric vehicles, including cars and trucks [14]. The simulation of charging battery truck using PV power can be observed in the Case B.

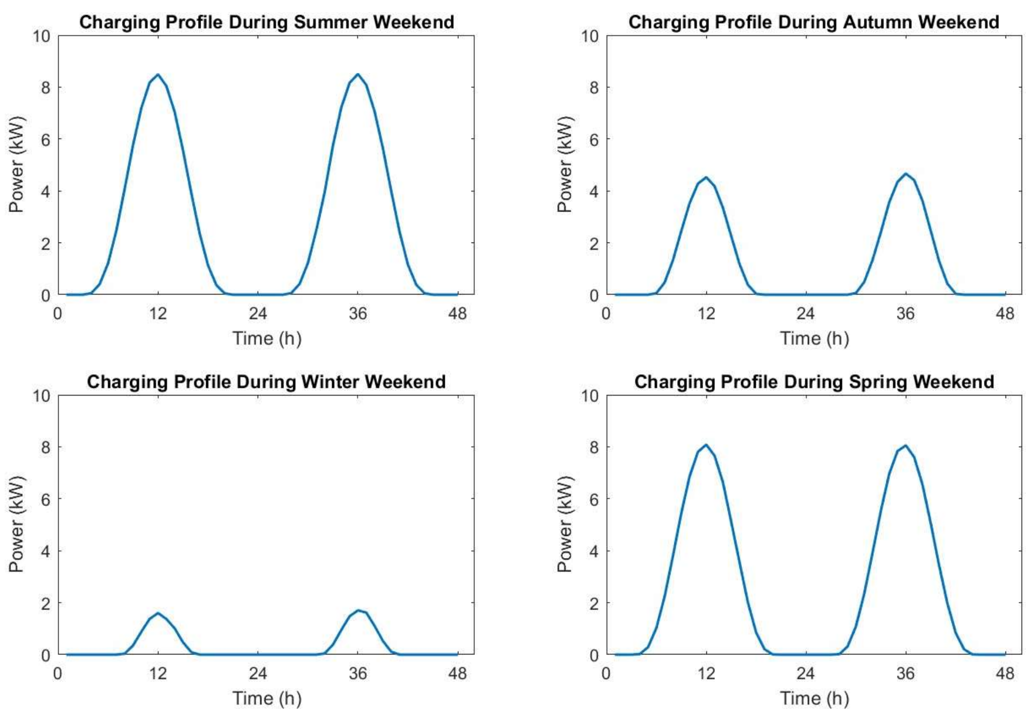



Figure 4. Battery charging load profiles of a hybrid-truck for Case B

Figure 4 shows that the battery charging profiles that obtained based on the PV profiles with mixed shading factors. Since the truck fleet will be modeled with mixed shading factors, as explained in the following section, the battery charging profiles shown in Figure *4* use PV profiles of 88.7% solar irradiance as the reference. This 88.7% value represents the average irradiance from four groups of 20 trucks, with irradiance levels of 100%, 90%, 85%, and 80%, respectively. Details of these mixed shading factors will be explained in the next section.

In Case B, the trucks will be charged by the PV system. Thus, the charging source of the batteries comes only from the power generated by the PV. The PV must produce power so that the battery can be charged, otherwise the charging power will be zero. As seen in Figure 3, the instantaneous output power of the PV of one hybrid truck never exceeds 50 kW. Therefore, it is expected that the truck battery will absorb all of the power from the PV. It is also expected that the power flow at the point of common coupling will be zero.

### 2.2.3 Integrating Solar Hybrid Truck into the Grid

Figure 5 shows the complete model of grid connected hybrid trucks. Since the aim of this project is to simulate a fleet of 80 trucks, it can be assumed that each truck receives different level of irradiation due to shading factor. In this simulation, the truck fleet is divided into 4 group parking lots to accomodate the different shading factors of the solar PVs. Figure 7 shows the total PV production of the fleet of 80 trucks with the shading factor taken into account.

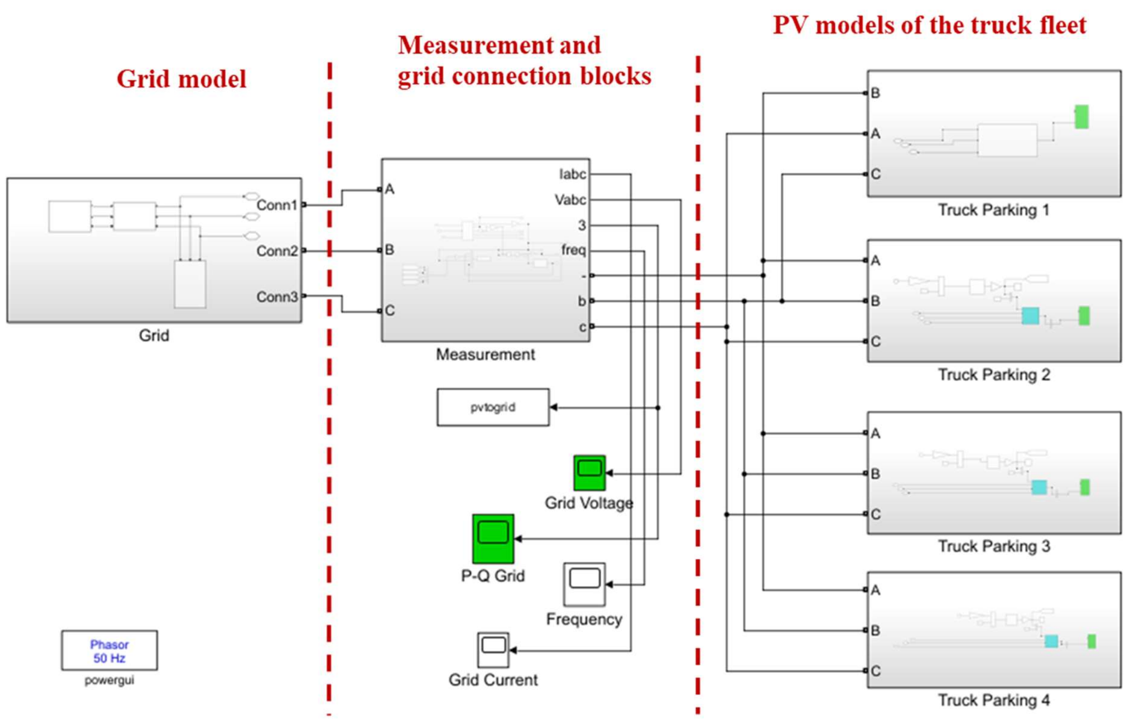
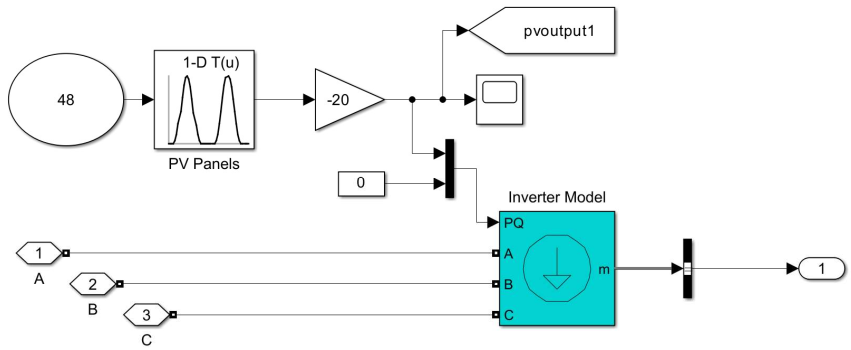



Figure 5. Model for the simulation of the grid connection of solar hybrid trucks in Simulink

Each parking group model includes both a PV panel model and a battery model. The scaled-up simulation models 80 hybrid trucks and uses irradiance data from SMHI (see Figure *3*). Different shading scenarios are applied for each season, resulting in varying levels of power production. The simulated cases are as follows:

- 100% irradiation level
- 90% irradiation level
- 85% irradiation level

- 80% irradiation level
- Mixed level of solar irradiation due to mixed shading factors. Each truck parking (consisting of 20 trucks) exposed to the various level of solar irradiation :
  Truck Parking 1 is exposed to 100% irradiation; Truck Parking 2 is exposed to 90% irradiation; Truck Parking 3 is exposed to 85% irradiation; and Truck Parking 4 is exposed to 80% irradiation.

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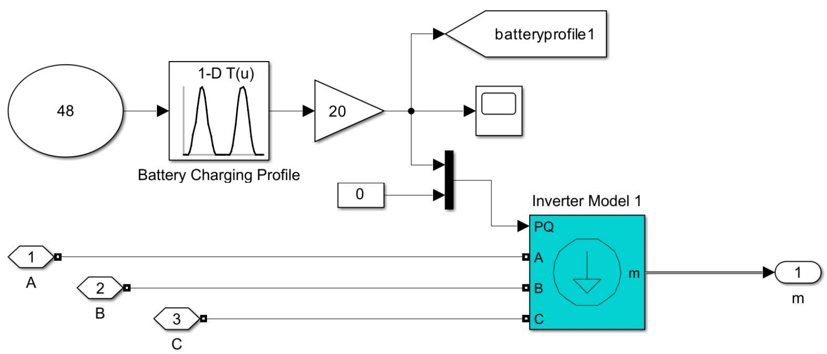



(b)

Figure 6. Model of (a) solar PV and (b) battery of the trucks for grid connecting simulation

In each truck parking subsystem shown in Figure 5, there are truck PV and truck battery model. Figure 6 shows the model of solar PV and battery of the trucks that are used in the grid connecting simulation. Three-phase dynamic load block is used to represent solar PV of a hybrid truck. This dynamic load block implements a three-phase load which active power vary as the input from the Lookup table block. Lookup table block itself calls the data of PV power output generated from solar PV generation model in Figure 2.

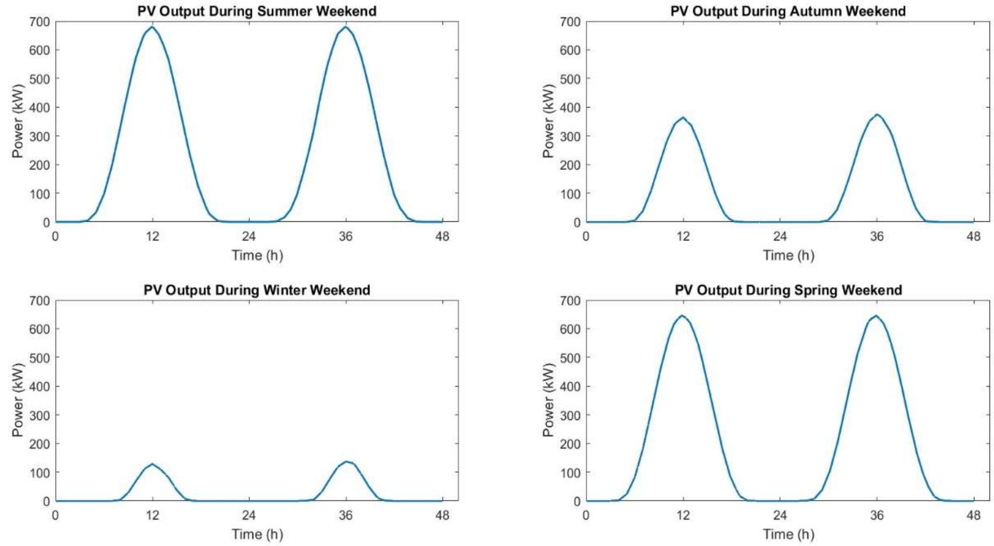



Figure 7. PV power profiles of 80 hybrid-trucks with mixed shading factors

## 2.3 Voltage Regulation

The integration of distributed energy resources (DER), such as solar PV, affects the performance of the grid [9]. In terms of quality, voltage regulation assessment is important to verify how the grid responds to the integration of DER. In this project, the hybrid trucks are recognized as DER because they have solar PV installed on them.

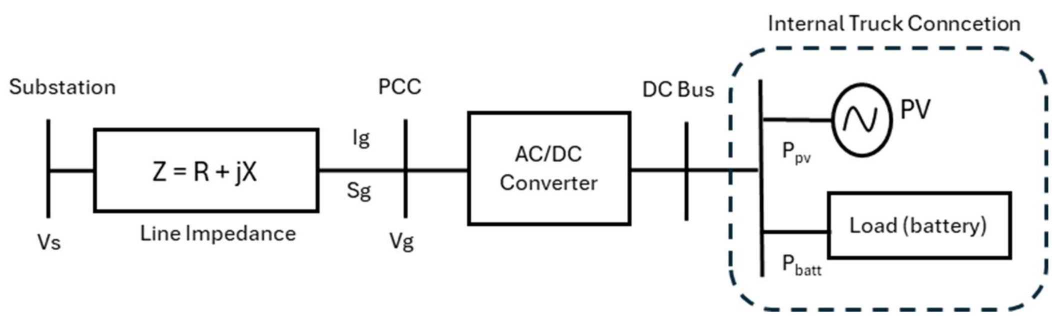



Figure 8. Connection diagram of hybrid trucks (with PV and battery installed)

Figure 8 shows that the solar PV on the trucks increases the complexity of the behavior between the trucks and the grid because the trucks have battery units on them due to the fact that they are electric vehicles. The voltage at the PCC, $V_g$ can be calculated :

$$V_g = V_s + I_g Z \quad (1)$$

$$I_g = {S_g^*}/{V_g^*} \quad (2)$$

Where,
$I_g$ is the current through the feeder,
$S_g$ is the apparent power injected by the trucks,
$P_{pv}$ is the power produced by PV,
$P_{batt}$ is the charging load of the battery unit,
R and X are the resistance and reactance of the feeder.

The fleet of hybrid trucks connected at point of common coupling through power electronic devices. Grid voltage rise is likely to occur when the amount of active power injected to the grid by DER, such as hybrid trucks. Voltage rise occurs during the period when generation of PV exceeds the load except some control and energy management mechanisms are implemented [15].

Observing the grid voltage is critical to analyzing the impact of connecting a fleet of hybrid trucks to the grid. The goal of this project is to see the impact of connecting a fleet of hybrid trucks to the grid. At least two cases are used in this project. The first case is evaluating the voltage increase when the PV production of a fleet of hybrid trucks is fully injected into the grid during their idle time. In this case, the grid connection point may become overvoltage. This condition can occur because the fleet of trucks operates as a distributed generator located at the edge of the distribution grid.

In the second case, when a fleet of discharged hybrid trucks is connected, it causes the grid operate in stressed condition. If a fleet of trucks connect to the grid as a load, the amount of PV production at that moment will compensate the battery load. The combination of PV production and battery load is observed in this case. Then, it is important to monitor the voltage drop of this charging mode of hybrid trucks. In this way, the distribution system operator can mitigate the operation of the grid in the face of the penetration of a fleet of hybrid trucks.

Table 2. Comparison of supply voltage requirements according to EN 50160 and the EMC standards EN 61000 [16]

| No | Parameter | Supply voltage characteristics according to EN 50160 | Low voltage characteristics according to EMC standard EN 61000 | |
|---|---|---|---|---|
| | | | EN 61000-2-2 | Other parts |
| 1 | Power frequency | LV, MV: mean value of fundamental measured over 10 s<br>±1% (49.5 - 50.5 Hz) for 99.5% of week<br>-6%/+4% (47- 52 Hz) for 100% of week | 2% | |
| 2 | Voltage magnitude variations | LV, MV: ±10% for 95% of week,<br>mean 10 minutes rms values (Figure 1) | | ±10% applied for 15 minutes |
| 3 | Rapid voltage changes | LV: 5% normal<br>10% infrequently<br>$P_{lt} \leq 1$ for 95% of week<br><br>MV: 4% normal<br>6% infrequently<br>$P_{lt} \leq 1$ for 95% of week | 3% normal<br>8% infrequently<br>$P_{st} < 1.0$<br>$P_{lt} < 0.8$ | 3% normal<br>4% maximum<br>$P_{st} < 1.0$<br>$P_{lt} < 0.65$<br>(EN 61000-3-3)<br>3% (IEC 61000-2-12) |
| 4 | Supply voltage dips | Majority: duration <1s, depth <60%.<br>Locally limited dips caused by load switching on:<br>LV: 10 - 50%, MV: 10 - 15% (Figure 1) | urban:<br>1 - 4 months | up to 30% for 10 ms<br>up to 60% for 100 ms<br>(EN 61000-6-1, 6-2)<br>up to 60% for 1000 ms<br>(EN 61000-6-2) |
| 5 | Short interruptions of supply voltage | LV, MV: (up to 3 minutes)<br>few tens - few hundreds/year<br>Duration 70% of them < 1 s | | 95% reduction for 5 s<br>(EN 61000-6-1, 6-2) |
| 6 | Long interruption of supply voltage | LV, MV: (longer than 3 minutes)<br><10 - 50/year | | |

The permissible voltage deviation ranges at common coupling in distribution grid are given in the EN 50160 standard as shown in Table 2. According to EN 50160, the voltage variation is allowed in the range of ± 10%. This standard is used as the main reference for voltage analysis in this project. However, utilities design the distribution system so as to maintain primary voltages within ± 5% of the nominal rating [17].

Since the project only focuses on the impact of the fleet of hybrid trucks when injecting power into the grid, the voltage profile of the grid before a fleet of hybrid trucks is connected is not considered. Therefore, this project limits the voltage variation range to ± 5% due to the safety factor.

## 2.4 Grid parameters

The connection of the hybrid trucks is located in Swedish existing power distribution grid infrastructure. This connection involves specialized equipment such as inverters to convert the direct current (DC) electricity generated by solar PV panels into alternating current (AC) electricity which is compatible with the grid.

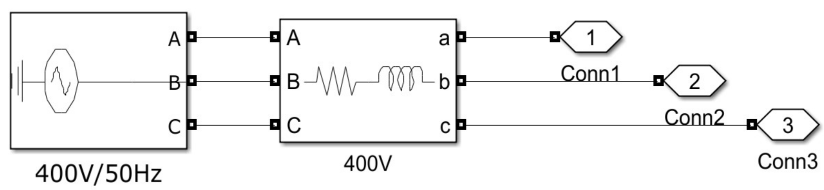



Figure 9. Grid Equivalent Model

Since the project aims to observe the amount of power can be injected into the existing grid, Figure 5 shows that the grid is represented by an equivalent model and the detailed model can be seen in Figure 9 below. Figure 9 shows the Simulink blocks consist of three-phase voltage source and RL impedance that represent the grid. The grid parameters shown in Table 3 are used to represent the distribution grid to which the hybrid truck fleet will be connected [19].

Table 3. Grid parameters

| Parameter | Value |
|---|---|
| Rated Line-to-Line Voltage (RMS) | 400 V |
| Rated System Frequency | 50 Hz |
| R/X Ratio of Grid Impedance | 0.69 |

## 2.5 Hosting capacity

The hosting capacity assessment is a crucial indicator that should be considered before connecting more PV systems to the grid. This project evaluates how the solar PV of the hybrid trucks affects the voltage quality of the distribution grid when all or some of the power produced by the trucks' PV panels is injected into the grid. If done properly, the hosting capacity assessment provides some information, including how many hybrid trucks can be accommodated without system upgrades and what issues arise at the hosting capacity limits [17].

The hosting capacity is considered when a fleet of hybrid trucks is plugged in with the fully charged batteries (90-100%). This condition affects all the power from PV is delivered to the grid. Thus, the grid voltage fluctuation as the impact of power injected by hybrid trucks to the grid becomes the constraint to determine the hosting capacity. The range ±5% is used as a constraint of hosting capacity calculation. Since the truck fleet is connected in 230.9 V of line-to-ground voltage grid, the grid voltage must be maintained between 218.5 V and 241.5 V.

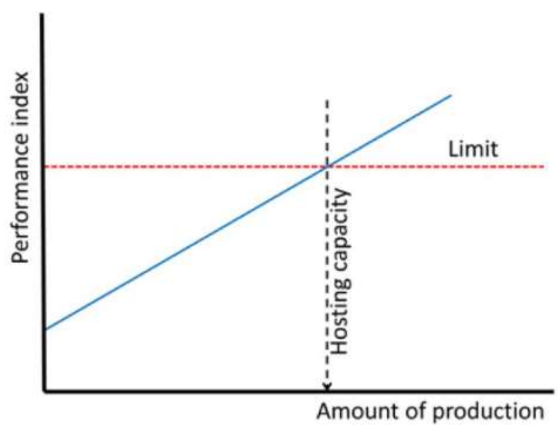



Figure 10. Basic Description of Hosting Capacity [10]

Figure 10 presents the basic definition of hosting capacity. In this project, the performance index will be the voltage of the grid with the limit of 5% above nominal voltage and the amount of production will be represented by the number of trucks.

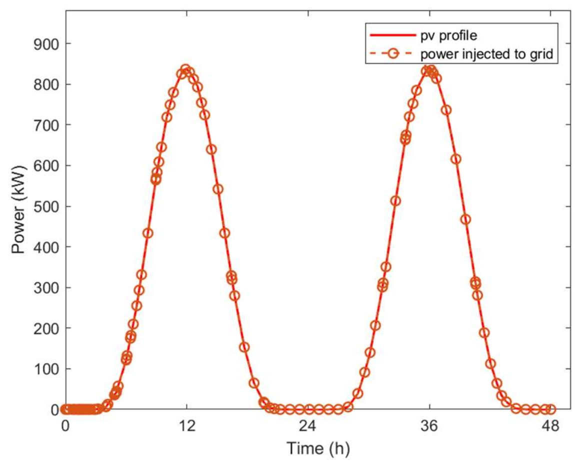
# 3. Results and Discussion

In this section, the results of simulations will be presented and some analysis will be discussed based on the results. Since the irradiation level varies by season, the results will be categorized by season to provide a complete overview of the interaction between a fleet of hybrid trucks and the distribution network throughout the year.

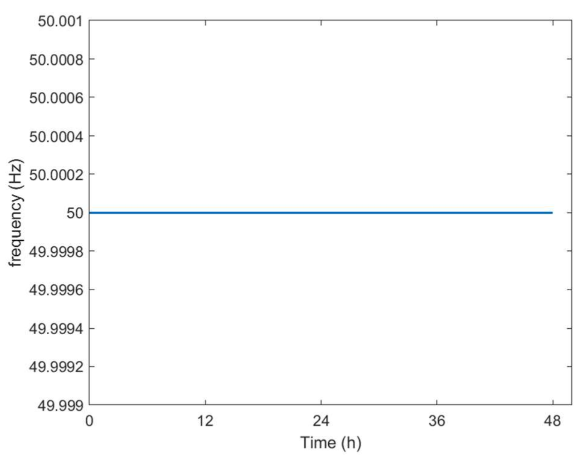
## 3.1. Study Case A – Grid injection of fully charged hybrid trucks

### 3.1.1 Summer

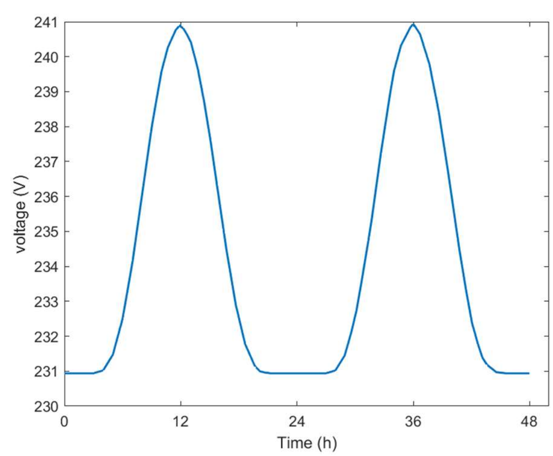
In Sweden, summer is the best time to harvest the solar energy and convert it into electricity. Table 1 indicates that under ideal temperatures and irradiation, the PV power of a hybrid truck can produce 13.7 kWp [8]. Figure 11 shows the total PV output of hybrid truck fleet based on irradiance level on 25-26 June 2024 and how much it can inject the grid. It shows that the maximum PV power produced by 80 hybrid trucks is about 840 kWp at the time around 12 pm in the afternoon.




(a) Total PV and Power Injected During Summer Weekend




(b) Grid Frequency

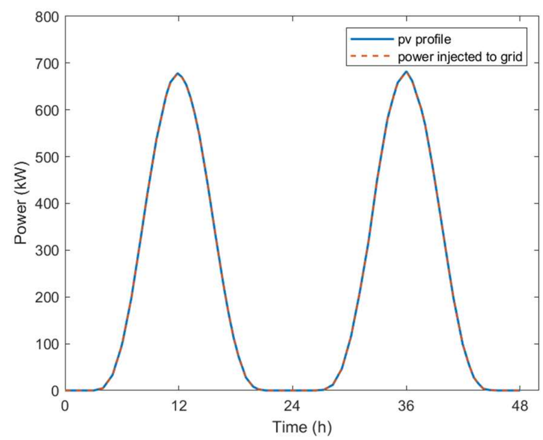



(c) Grid Voltage

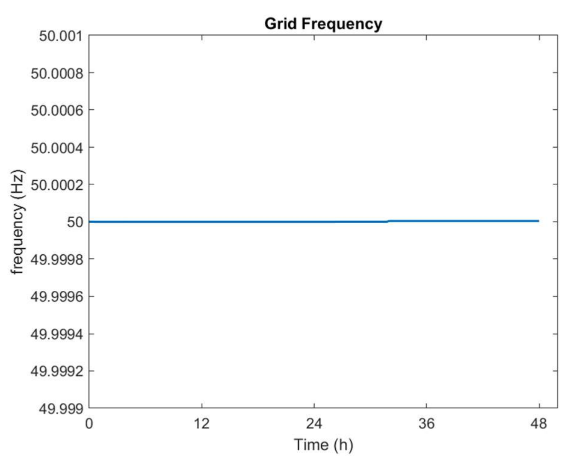
Figure 11. Simulation results when 80 trucks are connected to grid on summer weekend with 100% exposed sun

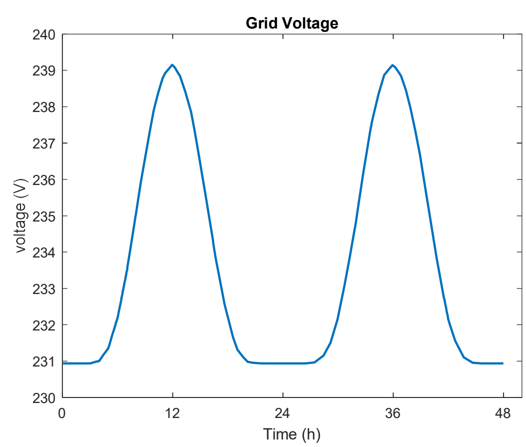
As mentioned before in the method section, one of the assumptions in study case A is that the batteries of the trucks are fully charged. Therefore, the entire PV production is supplied to the grid via PCC. With this assumption, it can be observed from Figure 11 that the PV power profile is exactly the same as the power injected profile. Similar to the PV production, the figure shows that the maximum power injected into the grid is about 840 kWp at 12 pm. Furthermore, this similar result will appear on the other seasons.

Since the plug-in infrastructure is connected to the strong interconnected grid, it is expected that the grid frequency will be hardly affected by injected power of the hybrid trucks. However, the situation is different when it comes to grid voltage. The grid frequency is a larger system issue, which means that the frequency in the bus connected to the Point of Common Coupling (PCC) is the same as the other all buses in the Swedish power grid. However, the grid voltage is a local issue that can be affected by the fluctuation of the power flow.




(a) Total PV and Power Injected During Summer Weekend




(b) Grid Frequency

(c) Grid Voltage

Figure 12. Simulation results when 80 trucks are connected to grid on summer weekend with mixed shading factors

Vita et al. (2015) discussed that connecting a distributed generation, such as PV, to a distribution grid can affect the improvement of voltage level [20]. Figure 12.a and Figure *12*.c show that the grid voltage increases when the PVs produce power, then the hybrid trucks supply the power to the grid. Since the peak PV production occurs at 12 pm each day, the highest grid voltage also occurs at the same time. Figure 12.c also shows that the highest grid voltage reached 239.1 V or 4% above the nominal line-to-neutral voltage of 230.9 V. This is less than 5%, the expected voltage fluctuation, and within the acceptable voltage range mentioned in Table 2. The complete result of all simulations for summer season can be seen in Table 4.

Table 4. Recap of simulation results on summer weekend

| Season | Number of trucks | Irradiance factor | Peak voltage (V) | Peak voltage (pu) | Max Power Inject (kWp) |
|---|---|---|---|---|---|
| Summer | 80 | 100% | 240.9 | 1.04 | 839 |
| Summer | 80 | 90% | 239.3 | 1.04 | 689 |
| Summer | 80 | 85% | 238.5 | 1.03 | 625 |
| Summer | 80 | 80% | 237.8 | 1.03 | 558 |
| Summer | 80 | mixed* | 239.1 | 1.04 | 679 |

* 20 trucks are exposed to 100% irradiation; 20 trucks to 90% irradiation; 20 trucks to 85% irradiation; and 20 trucks to 80% irradiation.

### 3.1.2 Autumn

PV production during autumn season is expected to be lower due to the reduced irradiation level and shorter daylight time. The results discussed in this section are based on the simulation using several different shading factors for a fleet of hybrid trucks.

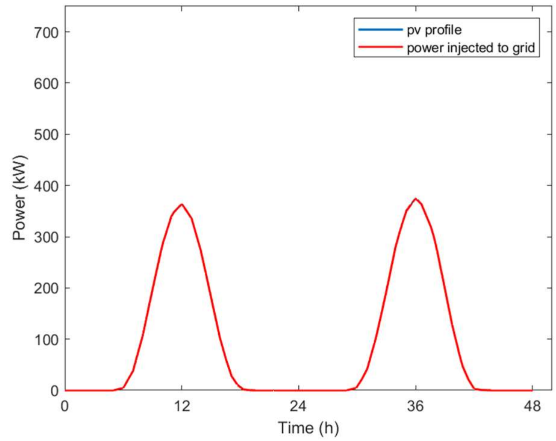
The graph in Figure 13 shows how much the PV production decreased in the autumn weekend. The figure presents the result based on the irradiance data of SMHI on 5-6 September 2024. The maximum PV power on the autumn weekend is only 55% of the maximum PV power on the summer weekend. Based on this result, the power injected into the grid also decreased by the same amount as shown in Figure 13.a.

Table 5. Recap of simulation results on autumn weekend

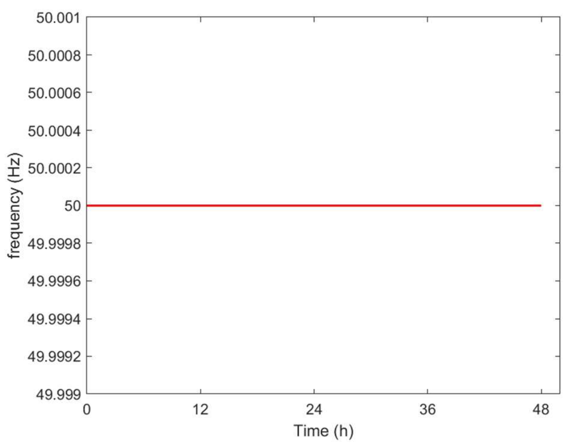
| Season | Number of trucks | Irradiance factor | Peak voltage (V) | Peak voltage (pu) | Max Power Inject (kWp) |
|---|---|---|---|---|---|
| Autumn | 80 | 100% | 236.6 | 1.02 | 462 |
| Autumn | 80 | 90% | 235.7 | 1.02 | 380 |
| Autumn | 80 | 85% | 235.2 | 1.02 | 343 |
| Autumn | 80 | 80% | 234.7 | 1.02 | 303 |
| Autumn | 80 | mixed* | 235.6 | 1.02 | 374 |

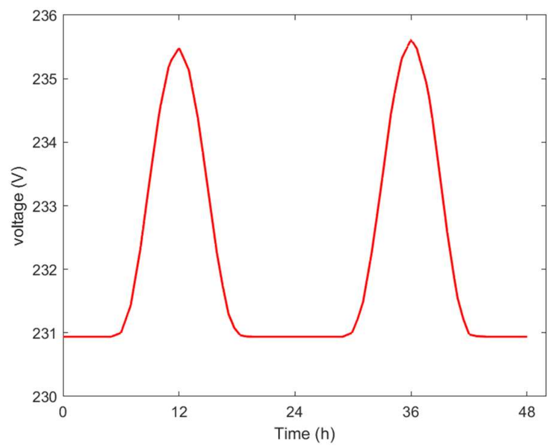
* 20 trucks are exposed to 100% irradiation; 20 trucks to 90% irradiation; 20 trucks to 85% irradiation; and 20 trucks to 80% irradiation.

The grid voltage rise in this case is also presented in Figure 13.c. The grid voltage increases to 235.6 V or 2% higher than the nominal voltage. This number is still in the acceptable voltage range. Figure 13.b also shows that the grid is quite strong as the frequency keeps stable in 50 Hz. The complete recap in Table 5 presents the results of all autumn weekend simulations.




(a) Total PV and Power Injected During Autumn Weekend



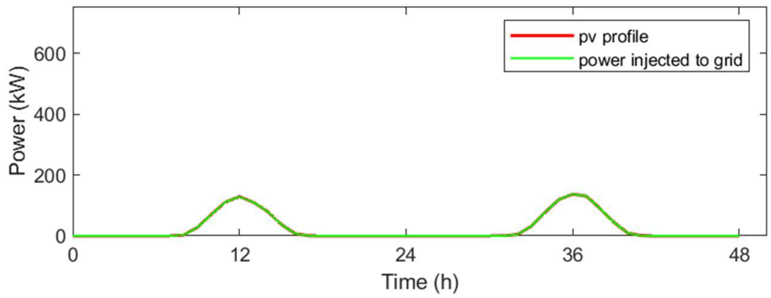

(b) Grid Frequency (c) Grid Voltage

Figure 13. Simulation results when 80 trucks are connected to grid on autumn weekend with mixed shading factors

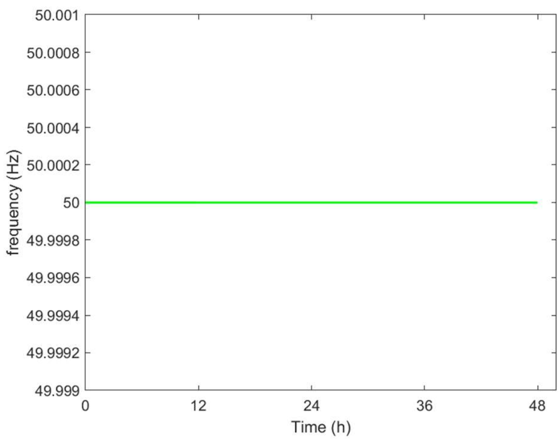
### 3.1.3 Winter

The fact that the lowest PV production occurs during winter season is hypothetically expected. The results presented in this section are derived from simulations that applied various shading factors to a fleet of hybrid trucks. With the provided irradiation level, temperatures, and daylight hours, the maximum PV power on the winter weekend is only 20% of the maximum PV power on the summer weekend as shown in Figure 14.a. The irradiance data of 19-20 February 2025 are used for this case. The figure shows the maximum power injected into the grid by the truck fleet is only reached 137 kWp.

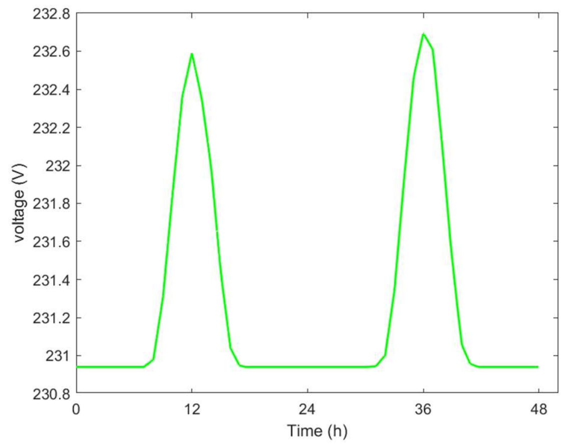
The reduction in power injected into the grid results in a decrease in grid voltage fluctuation. Figure 14.c shows that the highest voltage increase occurs to 232.7 V at 12 pm on both weekend days. This 1% deviation is still within the acceptable voltage range when the grid frequency is also in the stable state of 50 Hz. Then, Table 6 shows the recap of simulation results in various irradiation cases.




(a) Total PV and Power Injected During Winter Weekend




(b) Grid Frequency




(c) Grid Voltage

Figure 14. Simulation results when 80 trucks are connected to grid on winter weekend with mixed shading factors

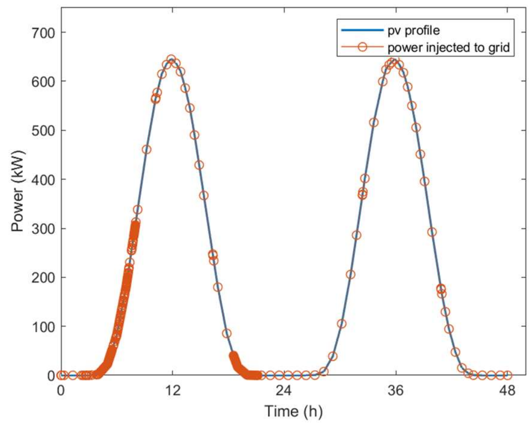
Table 6. Recap of simulation results on winter weekend

| Season | Number of trucks | Irradiance factor | Peak voltage (V) | Peak voltage (pu) | Max Power Inject (kWp) |
|---|---|---|---|---|---|
| Winter | 80 | 100% | 233.1 | 1.01 | 166 |
| Winter | 80 | 90% | 232.7 | 1.01 | 140 |
| Winter | 80 | 85% | 232.5 | 1.01 | 125 |
| Winter | 80 | 80% | 232.4 | 1.01 | 111 |
| Winter | 80 | mixed* | 232.7 | 1.01 | 137 |

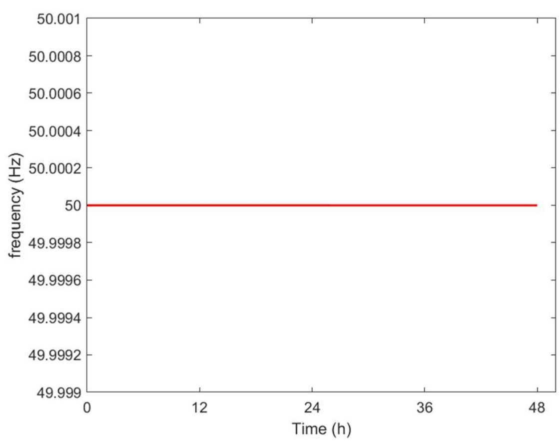
* 20 trucks are exposed to 100% irradiation; 20 trucks to 90% irradiation; 20 trucks to 85% irradiation; and 20 trucks to 80% irradiation.

### 3.1.4 Spring

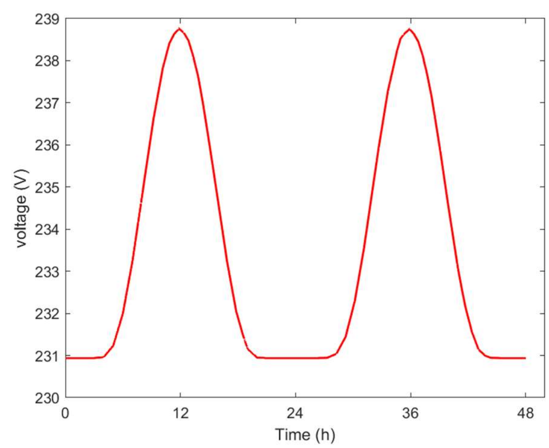
This section shows the results from simulations performed under varying shading factors for a fleet of hybrid trucks. Within this period, the PV production is enhanced compared to the winter and autumn months. The higher solar exposure to the PV panels contributes to the improvement of PV performance. The total PV production of truck fleet is shown in Figure 15.a. Although the irradiation level in spring season is not as high as in summer, the maximum PV power almost reached the same amount as in summer. The maximum PV power reached 577 kWp at around 12 pm. This number is about 95% of the maximum PV power in the summer weekend.




(a) Total PV and Power Injected During Spring Weekend




(b) Grid Frequency




(c) Grid Voltage

Figure 15. Simulation results when 80 trucks are connected to grid on spring weekend with mixed shading factors

Table 7. Recap of simulation results on spring weekend

| Season | Number of trucks | Irradiance factor | Peak voltage (V) | Peak voltage (pu) | Max Power Inject (kWp) |
|---|---|---|---|---|---|
| Spring | 80 | 100% | 240.5 | 1.04 | 800 |
| Spring | 80 | 90% | 238.9 | 1.03 | 660 |
| Spring | 80 | 85% | 238.2 | 1.03 | 593 |
| Spring | 80 | 80% | 237.4 | 1.03 | 532 |
| Spring | 80 | mixed* | 238.8 | 1.03 | 645 |

* 20 trucks are exposed to 100% irradiation; 20 trucks to 90% irradiation; 20 trucks to 85% irradiation; and 20 trucks to 80% irradiation.

The considerable number of power injected into the grid as provided in Figure 15.c affects the grid voltage increase 3% above nominal voltage, into 238.8 V. The grid voltage and frequency in the figure above indicates that both parameters are still stable within the acceptable normal voltage range. Furthermore, Table 7 presents the results of all simulation in spring season. The table summarizes the simulations with various shading factors in the truck fleet.

Table 8. Voltage conditions for Case A with mixed* shading factors

| Season | Number of trucks | Peak voltage (V) | Peak voltage (pu) | Max Power Inject (kW) |
|---|---|---|---|---|
| Summer | 80 | 239.1 | 1.04 | 679 |
| Autumn | 80 | 235.6 | 1.02 | 374 |
| Winter | 80 | 232.7 | 1.01 | 137 |
| Spring | 80 | 238.8 | 1.03 | 645 |

* 20 trucks are exposed to 100% irradiation; 20 trucks to 90% irradiation; 20 trucks to 85% irradiation; and 20 trucks to 80% irradiation.

## 3.2. Study Case B – Self charging of discharged hybrid trucks (50% SoC)

The simulation in Case B indicates that the battery capacity of the truck fleet is possible to absorb the entire PV production if the batteries are not fully charged. In this case, it is assumed that the batteries of the truck fleet are 50% discharged due to operational use.

Figure 16 indicates that all the power produced by the PV truck system is used to charge the truck batteries. This is because the 1 truck never produces more power than the maximum battery charging rate (50 kW). Figure 16 also shows that the power injected into the grid is always zero when the truck fleet is parked with the battery SoC at 50% or less. It happens because all the power produced by the PV is absorbed by the truck batteries. The only situation that can make the trucks inject the power into the grid is when the PV of the trucks can produce more than 50 kW or when the truck batteries are full.

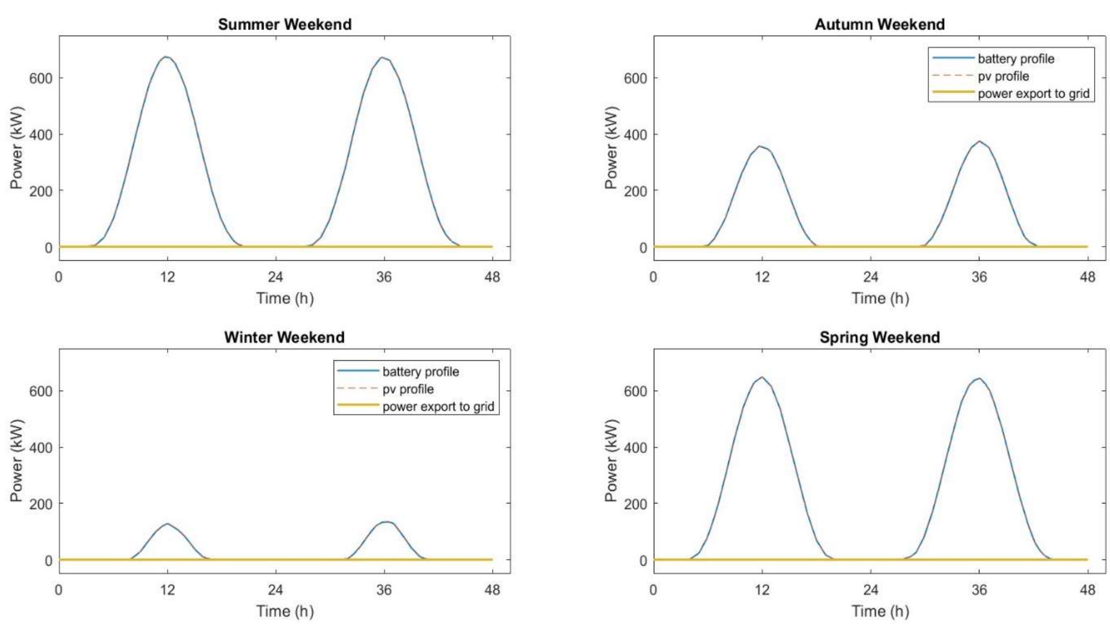



Figure 16. Grid connected hybrid truck power profile during weekend in different seasons

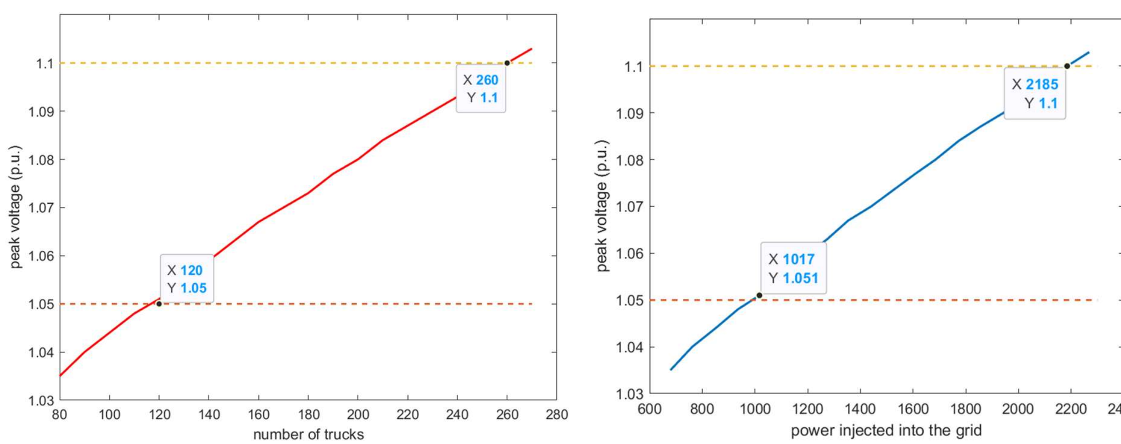
From Table 9, it can be seen that all batteries are assumed to be at 50% when they stop working on Friday and are parked during the idle period of the weekend. Table 9 also shows that the average SoC of the truck batteries can reach about 90% during the summer and spring periods. Therefore, it can be concluded that the truck batteries can be fully charged if they are charged during the weekend in the summer and spring seasons.

Table 9. PV production of 80 trucks and the SoC of the truck fleet after getting charged during weekend

| Season | PV production (kWh) | Peak power (kW) | Initial SoC | Final SoC |
|---|---|---|---|---|
| Summer | 10674.39 | 682.60 | 50% | 92% |
| Autumn | 4598.42 | 375.50 | 50% | 68% |
| Winter | 1216.53 | 137.19 | 50% | 55% |
| Spring | 9920.49 | 649.44 | 50% | 89% |

## 3.3. Hosting capacity assessment

Table 8 shows that the grid voltage never exceeds above 5% of nominal voltage in all seasons of the year. Since the concern is the increase in grid voltage, the impact of connecting the hybrid truck fleet in summer is the main consideration due to its amount of PV production. The worst case scenario for overvoltage analysis is represented in case A simulation because the amount of power injected into the grid can be observed in case A.



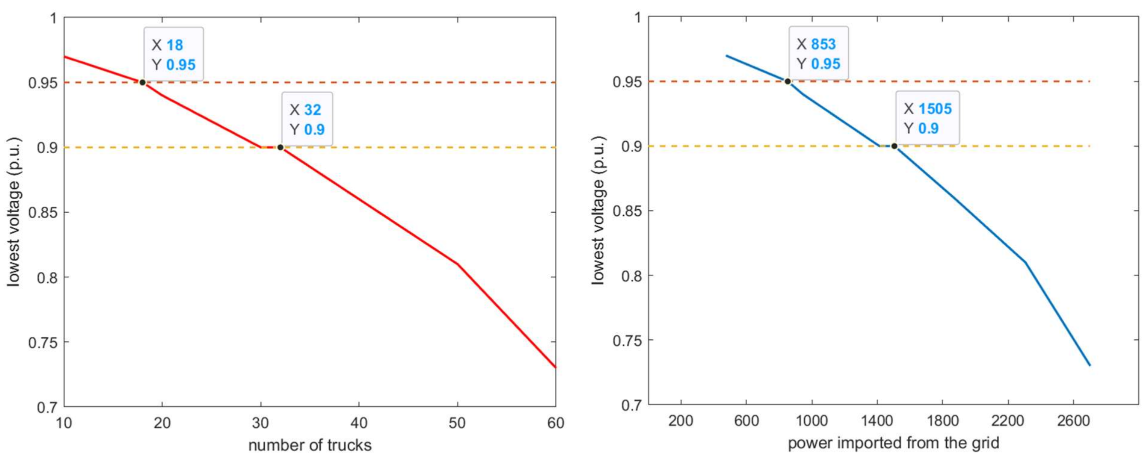

(a) (b)

Figure 17. Hosting capacity plot : (a) number of trucks connected vs peak voltage of the grid; (b) power injected vs peak voltage of the grid

As presented in Table 9, the highest PV production occurs in the summer and the lowest is in the winter. Since the hosting capacity assessment uses case A simulation, it is clear that the amount of power injected into the grid is the same as the PV production shown in Table 9. Thus, the results shown in Table 9 are in line with the peak voltage results in Table 8. The peak voltage increase occurs in the summer at 4% and the lowest occurs in the winter at 1%. As the voltage limit for distribution grid is ±5%, Table 8 shows that the fleet of 80 trucks does not violate the voltage quality of the connection bus.

Since the grid voltage does not exceed the acceptable range as shown in Table 8, there is an opportunity to improve the number of hybrid trucks to connect to the grid. If the grid voltage still becomes the only constraint, then the simulation of this case will add the number of trucks until the voltage exceeds the limit. Figure 17.a shows that the grid voltage starts to exceed the 5% limit when 120 hybrid trucks are connected to the grid. It can also be seen that the grid voltage reaches 10% above the nominal voltage when the truck fleet is expanded to 260 hybrid trucks.

If the thermal limitation on the grid such as distribution or transmission line is not considered as a constraint, a truck fleet can be expanded to inject the power into the grid up to 1017 kW before the grid voltage increases to the 5% above the nominal voltage. Figure 17.b also shows that the grid voltage at connection point reach 10% overvoltage when the power injected by the hybrid trucks increases to 2185 kW.




(a) (b)

Figure 18. Hosting capacity plot : (a) number of trucks connected vs lowest grid voltage; (b) power imported vs lowest grid voltage

In another scenario, when the PV panels are assumed to have zero output, the trucks are simulated as being charged directly from the grid. Assuming the rated power charge is 50 kW per truck, the result can be seen in Figure 18. As the number of charging trucks increases, the impact on the system voltage becomes more pronounced. When 18 trucks are charged at the same time, a voltage drop of approximately 5% is observed. This level of voltage deviation is typically near the upper limit of what is acceptable under most distribution standards, indicating that 18 trucks may represent a threshold near the system's hosting capacity.

Figure 18.a shows that when the number of hybrid trucks increases to 32, the voltage drop reaches 10%. This amount of voltage drop obviously exceeds acceptable limits for voltage fluctuation in distribution networks. This suggests that the system becomes significantly stressed, which could compromise power quality and reliability for other users connected to the same feeder.

# 4. Conclusion

From this project, it can be concluded that connecting solar hybrid truck to the distribution grid has an impact on voltage fluctuations that needs to be addressed. The focus of this project is to evaluate when the truck fleet injects the power that produced by its PV system. The project evaluates the voltage increase when the amount of power is injected into the grid.

The results of the simulations built in Simulink show that the highest impact occurs when the truck fleet is connected in the summer with fully charged batteries. Another simulation case when the truck batteries are not fully charged, shows that all the power produced by the PV truck systems can be absorbed to charge the truck batteries. The project also simulates to find maximum number of the hybrid trucks can be connected to grid before violating the grid voltage limit.

## 4.1 Future Work

This project has provided valuable insights into voltage fluctuations caused by the power injection of hybrid trucks into the distribution grid. However, several areas require further study. For example, future studies could explore more detailed modeling that integrates real-world driving and charging schedules of the truck fleet. This could provide a more dynamic understanding of power injection timing and battery charging behaviors.

Since this project only observed battery charging using power produced by the trucks' PV systems, future studies could consider truck battery charging by importing power from the grid. Simulating this type of case in future studies would allow for a more comprehensive observation of the grid impact caused by hybrid trucks.

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# Appendix

## A. Result for Summer weekend with different irradiance level

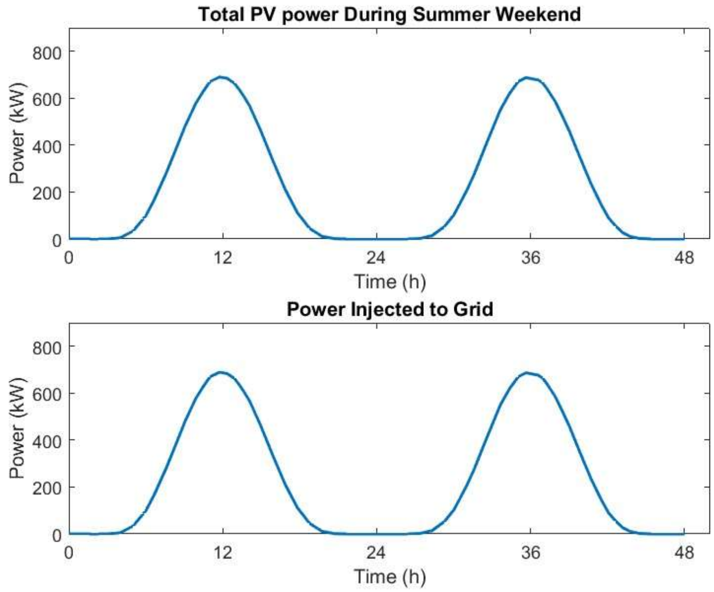


Figure 19. PV power of 80 trucks and power injected to grid during summer weekend with 90% exposed sun

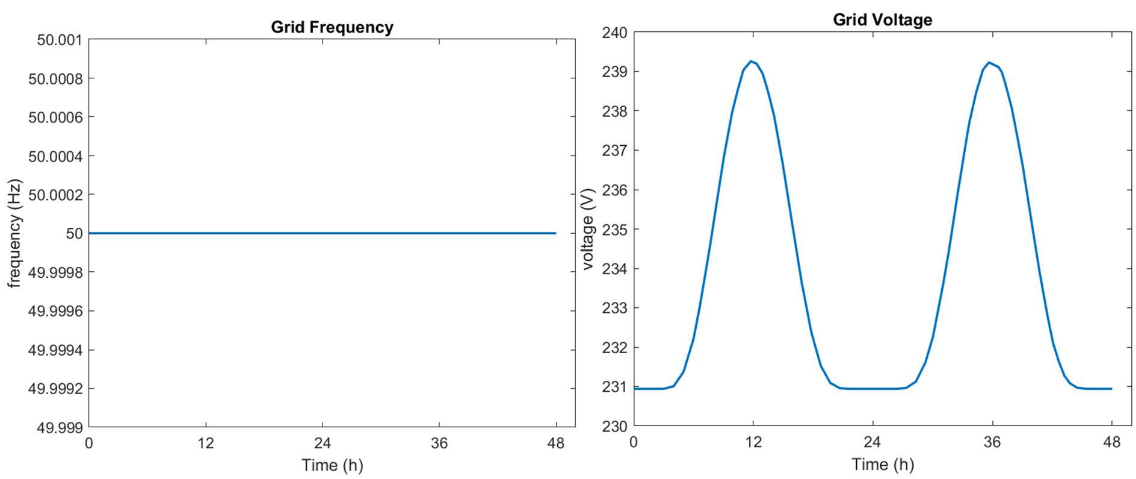


Figure 20. Grid frequency and voltage when 80 trucks are connected to grid on summer weekend with 90% exposed sun

Figure 19 and Figure 20 present the result of simulation using 90% of summer irradiance level from SMHI. With this irradiance level, the power injected into the grid can reach 689 kWp and the grid voltage can reach 239.3 V. The decrease in the amount of power injected obviously makes the frequency keep stable in 50 Hz.

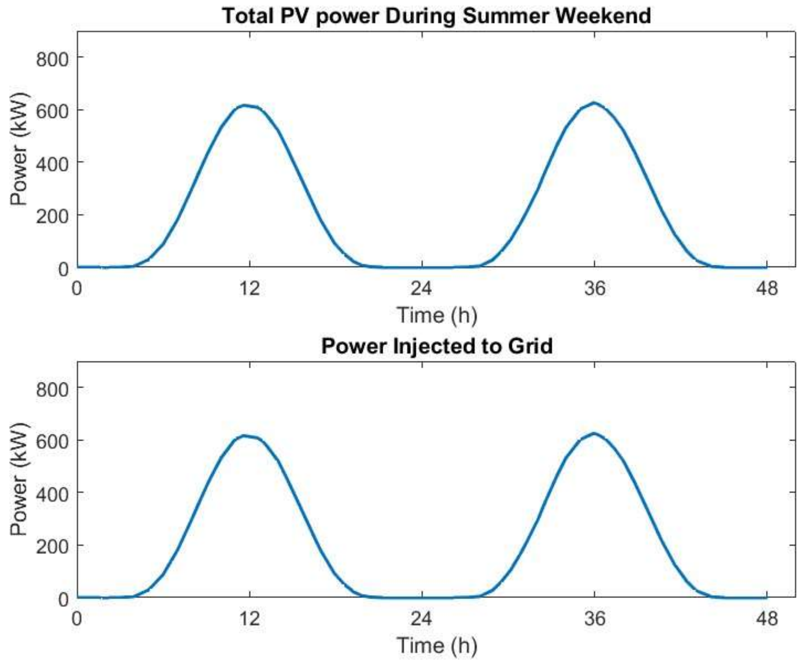


Figure 21. PV power of 80 trucks and power injected to grid during summer weekend with 85% exposed sun

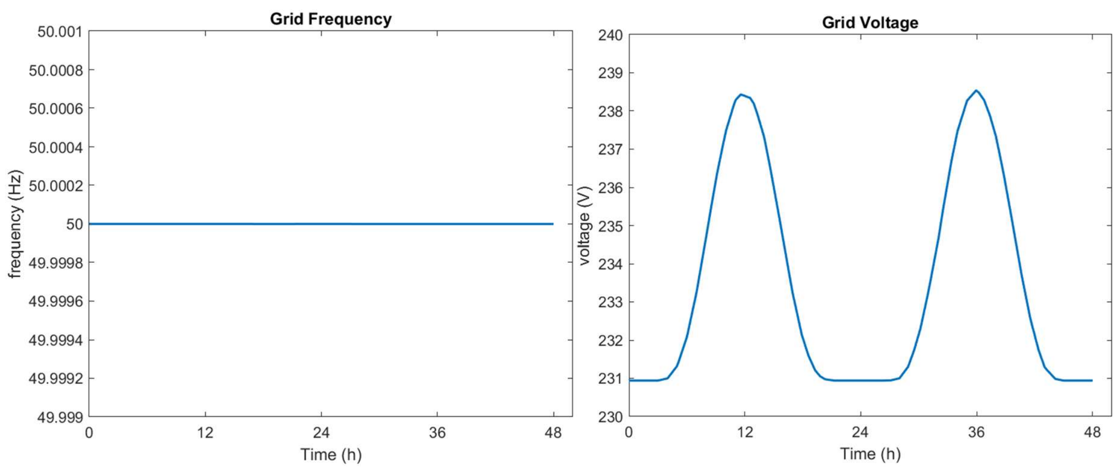


Figure 22. Grid frequency and voltage when 80 trucks are connected to grid on summer weekend with 85% exposed sun

Figure 21 and Figure 22 present the result of simulation using 85% of summer irradiance level from SMHI. Figure 21 shows the power injected into the grid can reach 625 kWp. Figure 22 shows the grid voltage can reach 238.5 V and this amount of power injected does not affect the grid frequency.

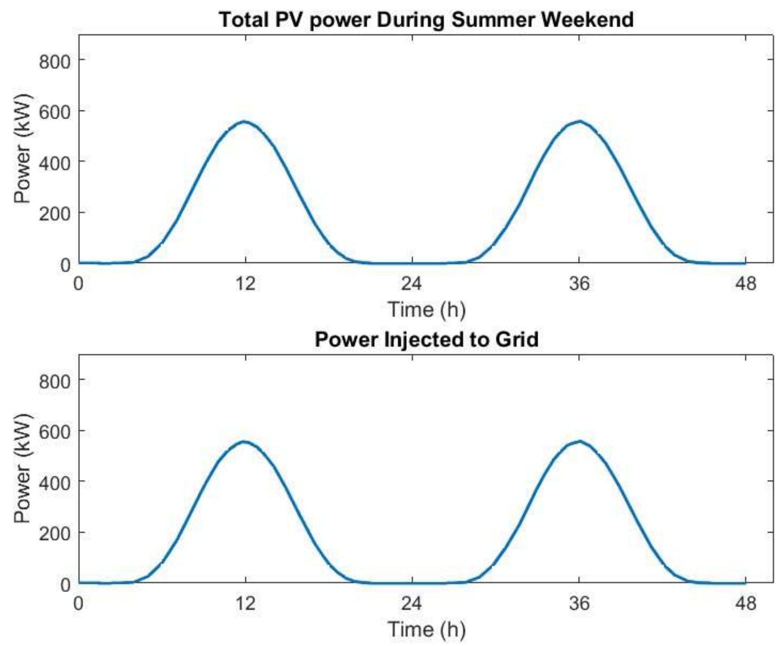


Figure 23. PV power of 80 trucks and power injected to grid during summer weekend with 80% exposed sun

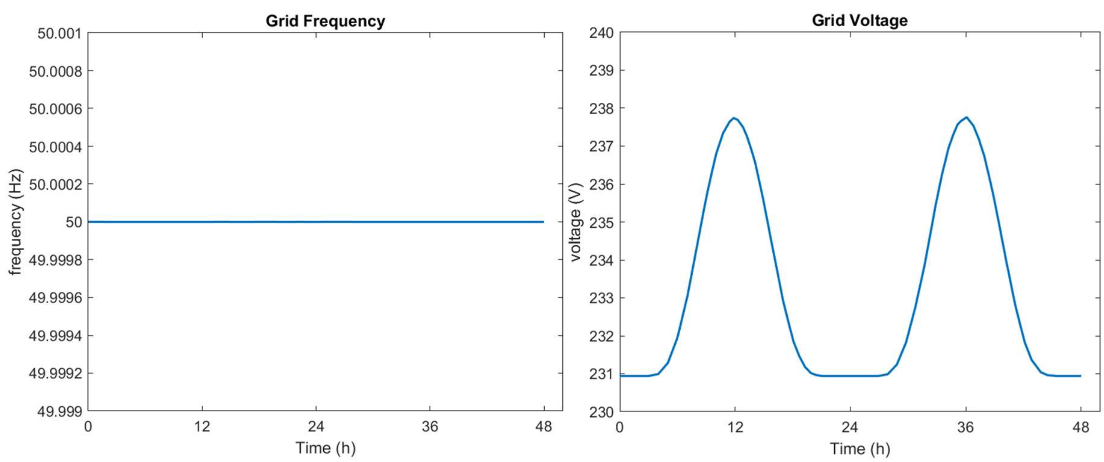


Figure 24. Grid frequency and voltage when 80 trucks are connected to grid on summer weekend with 80% exposed sun

Figure 23 and Figure 24 shows the result of simulation using 80% of summer irradiance level from SMHI. With this irradiance level, the power injected into the grid can reach 558 kWp and the grid voltage can reach 237.8 V. When the power injected decrease, the impact to the grid frequency gets lower and frequency keep stable in 50 Hz.

## B. Result for autumn weekend with different irradiance level

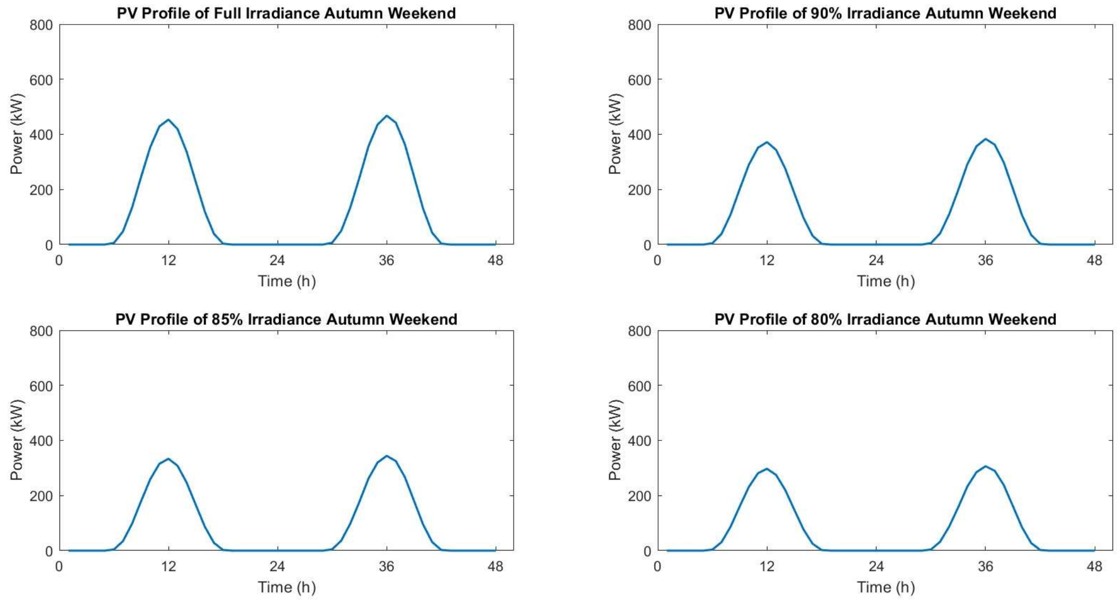


Figure 25. PV profiles of 80 trucks in autumn weekend

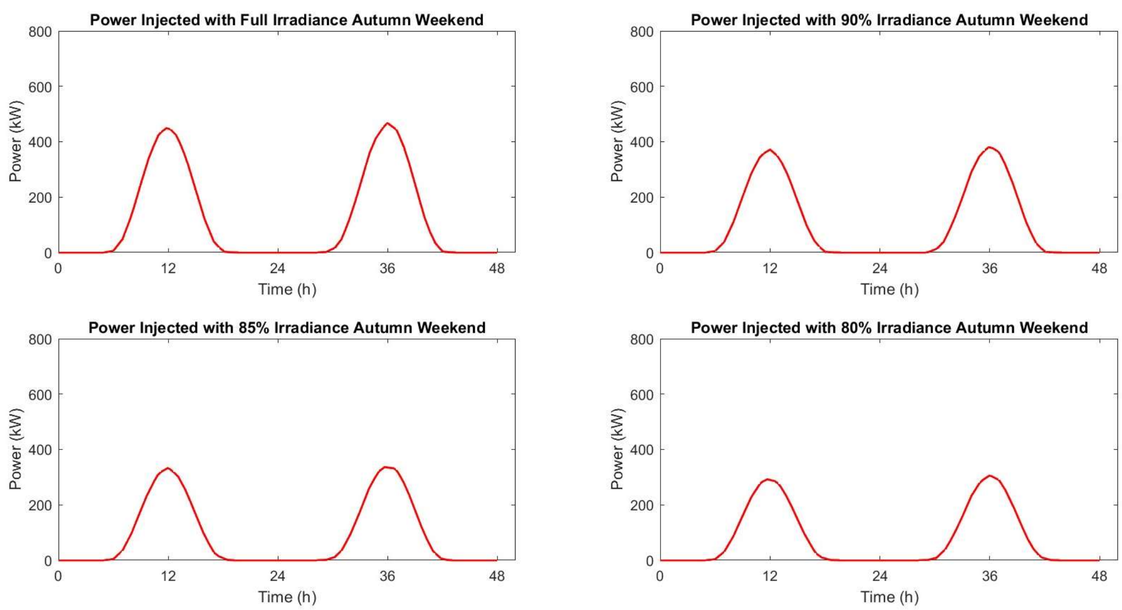


Figure 26. Power inject of 80 trucks into the grid in autumn weekend

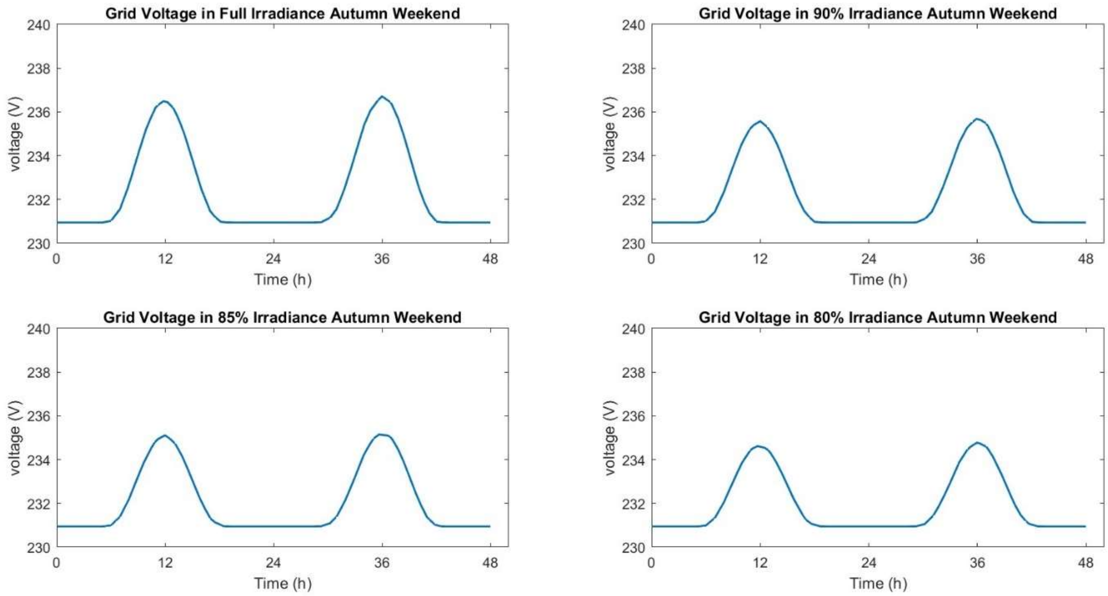


Figure 27. Grid voltage in autumn weekend

# C. Result for winter weekend with different irradiance level

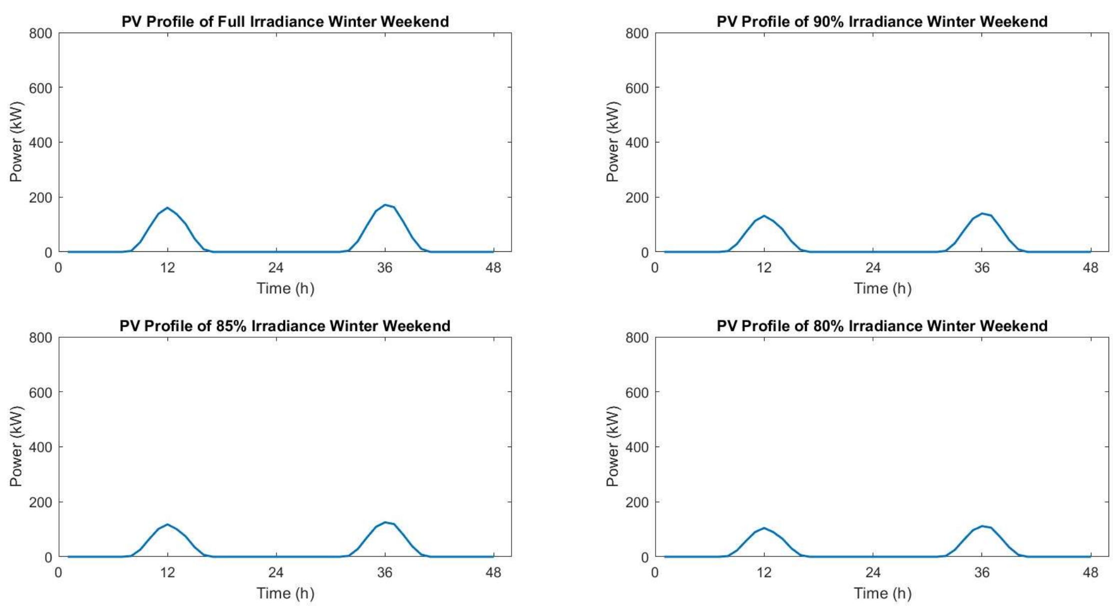


Figure 28. PV profiles of 80 trucks in winter weekend

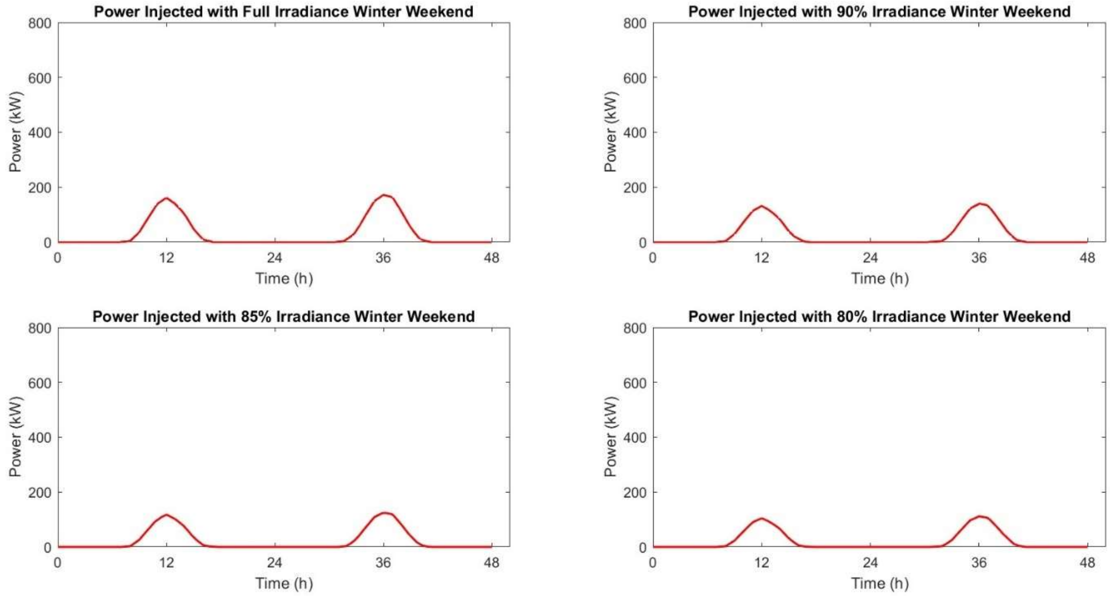


Figure 29. Power inject of 80 trucks into the grid in winter weekend

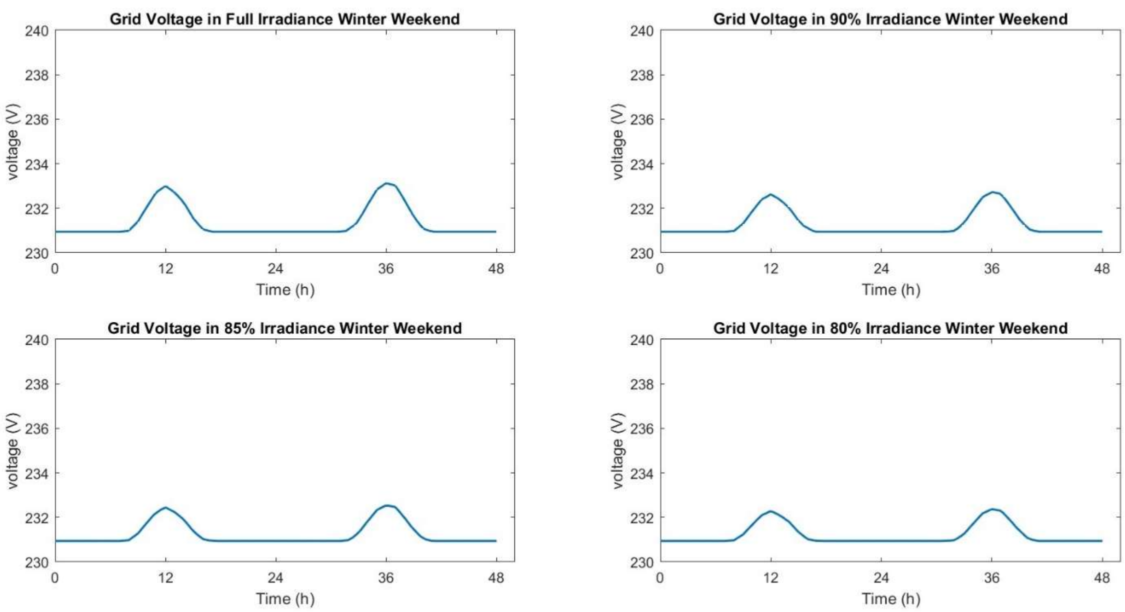


Figure 30. Grid voltage in winter weekend

## D. Result for spring weekend with different irradiance level

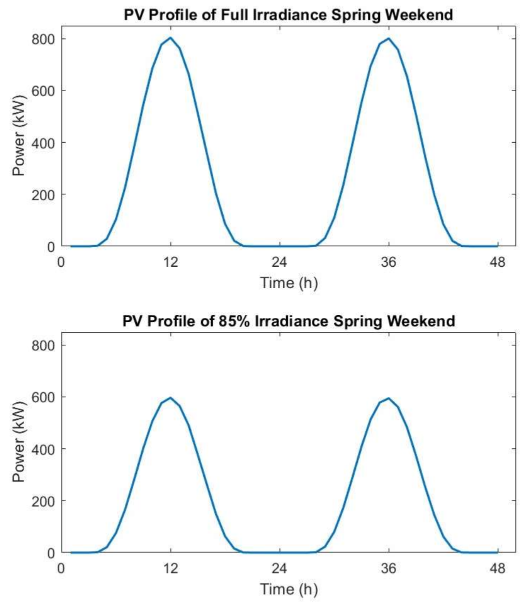


Figure 31. PV profiles of 80 trucks in spring weekend

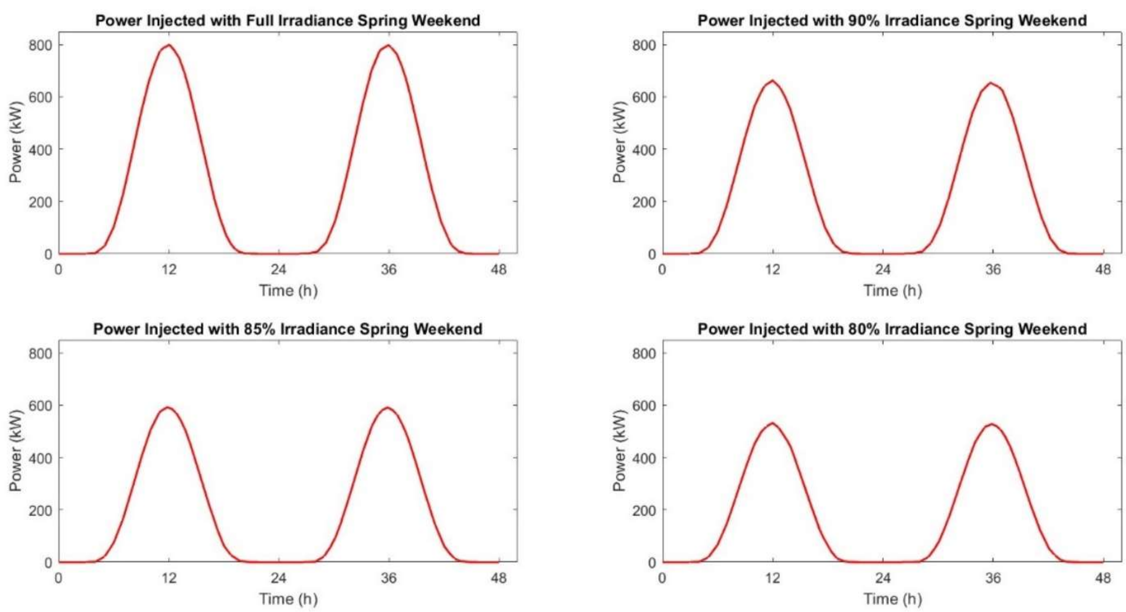


Figure 32. Power inject of 80 trucks into the grid in spring weekend

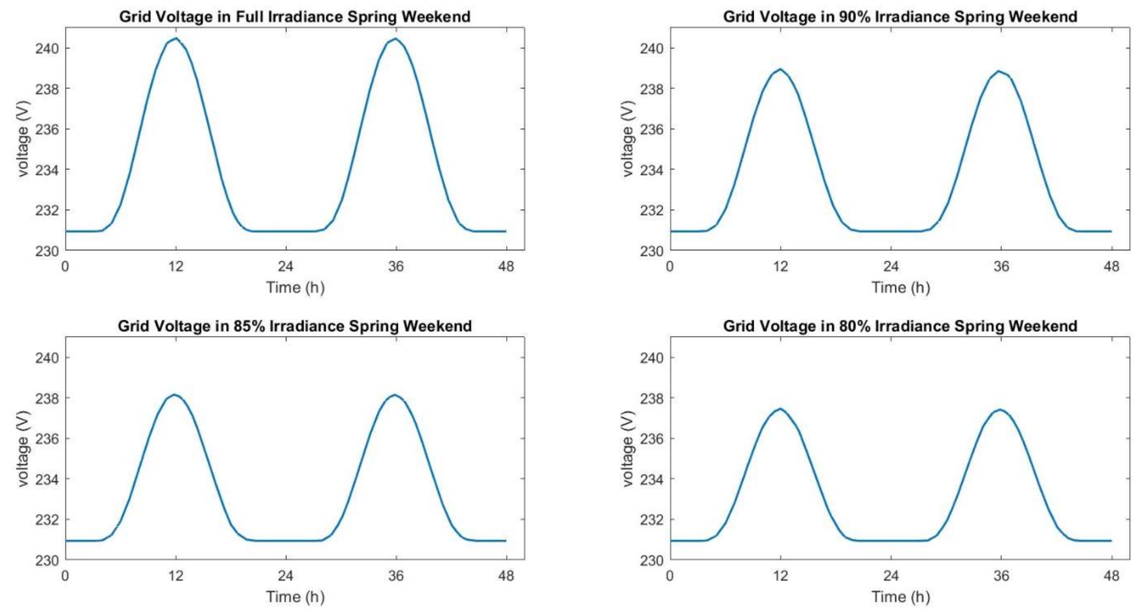


Figure 33. Grid voltage in spring weekend