Assessment of sustainable charging operations of Mekante Diek's construction equipment

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Samenvatting

Dit onderzoek betreft een bouwproject dat zich richt op de dijkversterking tussen Tiel en Waardenburg. De samenwerkende partijen in dit project—Ploegam, Dura Vermeer en Van Oord (gezamenlijk bekend als Mekante Diek)—willen het dijkversterkingsproject zo duurzaam mogelijk uitvoeren. Onder andere is besloten om het dijkversterkingsproject grotendeels uit te voeren met emissievrije (Zero Emissie, ZE) machines. Daarmee is het een van de eerste grootschalige bouwprojecten in Nederland die grotendeels met ZE-machines en ZE-voertuigen wordt uitgevoerd. Het Mekante Diek project richt zich ook op het creëren van een praktische, duurzame en betaalbare laadinfrastructuur voor bouwplaatsen. Hiervoor is door WattHub een laadplein ontwikkeld nabij de dijkversterkingslocatie.

Het WattHub-laadplein beschikt over 36 DC-laadpunten (gelijkstroom) met een capaciteit van maximaal 400 kW per laadpunt. Daarnaast zijn er zes AC-aansluitingen (wisselstroom) die tot 250 kW kunnen leveren. Het laadplein is direct verbonden met drie windturbines en indirect verbonden met een zonnepark, waardoor hernieuwbare energie direct kan worden gebruikt tijdens het laden. Bij afwezigheid van energie uit deze bronnen zorgt een netaansluiting voor elektriciteit naar het laadplein. Hoewel de laadfaciliteiten bij WattHub voornamelijk het elektrische bouwmaterieel voor het dijkversterkingsproject ondersteunen, kunnen ook externe partijen gebruik maken van de faciliteit.

Het primaire doel van dit onderzoek is het analyseren van de operationele efficiëntie en duurzaamheidsimpact van het ZE-materieel van Mekante Diek in combinatie met het laadplein van WattHub. Hierbij wordt ook ingegaan op de verschillende factoren die de prestaties van het opladen van het ZE-materieel bij WattHub beïnvloeden. De bevindingen in deze rapportage zijn grotendeels bepaald op basis van verzamelde praktijkdata.
Het onderzoek is een samenwerking tussen TNO en Mekante Diek, ondersteund door een subsidie van de Rijksdienst voor Ondernemend Nederland (RVO) in het kader van de Subsidieregeling Schoon en Emissieloos Bouwmaterieel Innovatie (SSEB Innovatie).

Het onderzoek concludeert dat het ZE-materieel dat in het Mekante Diek-project worden gebruikt, en geladen bij WattHub, aanzienlijke energiebesparingen en emissiereducties biedt. Met de combinatie van hernieuwbare energie, een innovatieve laadinfrastructuur en de inzet van duurzaam materieel, wordt aangetoond dat grootschalige bouwprojecten mogelijk zijn met ZE-materieel op een duurzame manier. Desalniettemin zijn er mogelijkheden om de laadefficiëntie te verbeteren. Het optimaliseren van laadschema's, het uitbreiden van opslagcapaciteiten en het verfijnen van het energiereserveringssysteem kunnen de prestaties van het laadplein verbeteren en het gebruik van hernieuwbare energie maximaliseren.

<u>Belangrijkste bevindingen</u>

<u>Energiegebruik van ZE-materieel:</u> Er zijn in deze studie gegevens verzameld over het energiegebruik van het toegepaste ZE-materieel in het project. Dit gaat onder andere over graafmachines, tractoren, vrachtwagens en kranen. Dataverzameling is een uitgebreid proces. Dit wordt beïnvloed door de verscheidenheid aan materieel die elk met verschillende methoden gegevens aanleveren.

Er is een aanzienlijke variabiliteit in energiegebruik geobserveerd bij het ingezette ZE-materieel. Het energiegebruik is met name afhankelijk van het type apparatuur en de werklast. Graafmachines gebruikten bijvoorbeeld tussen de 50 en 85 kWh aan energie per uur, terwijl tractoren tussen de 12,5 en 31 kWh per uur gebruikten. Het energiegebruik van de ZE-vrachtwagens voor bouwtransport was tussen de 1,8 en 2,4 kWh per km, waarbij vrachtwagens die worden gebruikt voor batterijtransport iets meer energie nodig hadden. Het wordt aanbevolen om het energiegebruik uitgebreider te monitoren en dit verbruik te koppelen aan activiteiten. Dit kan helpen om het energiegebruik voor de komende bouwperiodes beter te voorspellen.

<u>Laadinfrastructuur bij WattHub</u>: WattHub laat zien dat het een effectieve laadlocatie is voor vrachtwagens, bouwmaterieel en verwisselbare batterijen. Het voldoet aan de ontwerpdoelstellingen door een toegankelijke opstelling te bieden. Zo kunnen batterijen veilig naast laders worden geplaatst zonder complexe manoeuvres. De huidige energiecontracten en infrastructuur leveren betrouwbaar en voldoende energie voor het Mekante Diek-project. 90% van de stroom van WattHub is direct afkomstig van het windpark. De resterende 10% komt vanuit het elektriciteitsnet. Slechts 15% van de beschikbare windenergie wordt tot nu toe benut, daarmee is er een aanzienlijk groeipotentieel. Er zijn enkele inefficiënties in het laadproces geïdentificeerd. De laadsessies werden vaak niet optimaal benut. Puur tijdsmatig zorgen laadsessies voor 30% benutting van het laadplein. Tijdens de laadsessies werd echter niet continu geladen, waardoor de daadwerkelijke laadtijd slechts 13% is. Dit geeft aan dat er mogelijkheden zijn om de efficiëntie van het laadproces te verbeteren. Voorgestelde strategieën omvatten gepland en langzaam laden, waarbij het laadvermogen wordt aangepast op basis van de verwachte eindtijd van de laadsessie.

<u>Laadkarakteristieken van Mekante Diek bij WattHub</u>: WattHub bedient meerdere klanten, waarbij het Mekante Diek-consortium (ten tijde van het onderzoek) goed is voor ongeveer 90% van het energiegebruik. De energiebehoefte van het Mekante Diek-consortium voor DC-laden komt voort uit drie hoofdbronnen: Powerboxen (wisselbare 140 kWh batterijen), Megaboxen (wisselbare 400 kWh batterijen) en vrachtwagens (450-540 kWh). In juni 2024 waren de Megaboxen verantwoordelijk voor 50% van het energiegebruik, vrachtwagens droegen 35% bij en de resterende vraag werd gedekt door de Powerboxen. De mediane laadniveaus per gebeurtenis waren 275 kWh voor Megaboxes, 90 kWh voor Powerboxes en 150 kWh voor vrachtwagens, met hogere waarden die meestal werden geobserveerd tijdens nachtelijke laadsessies. De AC-lader werd daarnaast gebruikt voor het laden van de batterijcontainers.

<u>Laadgedrag:</u> Laadprofielen verschillen sterk bij de verschillende apparatuur. Het laden van de Powerboxen piekt tussen 11.00 en 16.00 uur, terwijl de Megaboxen twee piekperiodes kennen in de ochtend en middag. Het laden van de vrachtwagens is breder verspreid, met veel activiteit rond 16.00 uur, waarschijnlijk ter voorbereiding op de operaties van de volgende dag. Deze profielen laten de variabiliteit in energiegebruik van het materieel zien wat sterk beïnvloed wordt door operationele eisen. Daarnaast laat het de afwezigheid van een basisbelasting tijdens nachten en weekenden zien, wat een kans is om een meer gebalanceerd en efficiënt laadschema te implementeren. Het vervroegen van het laden van batterijcontainers naar eerdere tijdslots kan bijvoorbeeld helpen om de ochtendpiek te verlichten en het algehele energiebeheer te verbeteren.

<u>Energievoorspelling:</u> De weersvoorspelling heeft een zeer belangrijke rol bij het optimaliseren van laadschema's bij WattHub. Machines en voertuigen kunnen kansen missen om op te laden tijdens periodes van hogere beschikbaarheid van windenergie.

Het integreren van weersvoorspellingen in laadstrategieën kan het gebruik van hernieuwbare energie, met name windenergie, verbeteren. Apparaten die voor langere perioden zijn aangesloten, zoals die aan het einde van de dag rond 16.00 uur of op vrijdagen zijn ingeplugd, zijn goed geschikt voor vertraagd laden tijdens tijden van hoge wind beschikbaarheid. Korte termijn weersvoorspellingen (tot vier dagen) kunnen efficiëntere planning mogelijk maken. Hiermee kan het gebruik van windenergie gemaximaliseerd worden, en de afhankelijkheid van netenergie verminderd worden.

Optimaliseren van energiegebruik bij WattHub: De analyse van verschillende laadstrategieën - via simulatie - om het energiegebruik bij WattHub te optimaliseren, toonde aan dat het verschuiven van nachtelijke laadsessies naar andere tijden kan helpen bij het beheren van piekbelastingen. Deze strategieën verminderden echter niet significant de stroom vanuit het net, of verhoogden niet significant het windenergiegebruik vergeleken met de huidige aanpak. Verdere strategieën, zoals het verschuiven van de energievraag overdag, of het focussen op nachtelijk laden in lijn met windpieken, kunnen mogelijk helpen, maar konden binnen de scope van dit project niet gesimuleerd worden. Hierbij dient ook rekening gehouden te worden met operationele haalbaarheid van dit soort strategieën.
In het bijzonder kan het gelijkmatiger spreiden van het laden gedurende de nacht en het aanpassen van het laadgedrag op basis van windvoorspellingen de afhankelijkheid van het net verminderen en het gebruik van hernieuwbare energie optimaliseren.

Impact op (vermeden) emissies: Een belangrijk voordeel van het gebruik van ZE-materieel is de vermindering van emissies. Het onderzoek heeft ZE-materieel vergeleken met conventioneel materieel. Voor het conventionele – dieselaangedreven – materieel is daarbij gerekend voor verschillende leeftijdscategorieën (oud, middelbaar en modern). Door de toepassing van ZE-materieel worden zowel de CO_2- als verontreinigende emissies (NO_x en PM) aanzienlijk vermindert. Oud conventioneel materieel zou bijvoorbeeld 12.000 kg NO_x en 948 kg PM per jaar uitstoten op dit bouwproject, moderne diesel aangedreven machines verminderen deze emissies tot 630 kg NO_x en 8 tot 40 kg PM. Met ZE-materieel worden deze (uitlaat)emissies volledig vermeden. Bovendien helpt ZE-materieel de aanzienlijke CO_2-emissies (ongeveer 940 ton per jaar) te vermijden.

Summary

This study concerns a project which focuses on the reinforcement of the dike between Tiel and Waardenburg. The collaborating parties in this project—Ploegam, Dura Vermeer, and Van Oord (collectively known as Mekante Diek)—are committed to executing this project as sustainable as possible. Among others, it has been decided to carry out the dike reinforcement project by using zero-emission (ZE) machinery as much as possible. It is one of the first large-scale construction projects in the Netherlands to be executed largely with ZE machines and vehicles. The Mekante Diek project also focuses on creating a practical, sustainable, and affordable charging infrastructure for construction sites. For this purpose, a charging hub was developed by WattHub in Geldermalsen, located near the dike reinforcement site.

The WattHub charging hub features 36 DC charging stations with a capacity of up to 400 kW each and six AC connections for container batteries, capable of delivering up to 250 kW. It is directly connected to three wind turbines and indirectly connected to a solar farm, providing renewable energy for operations. In the absence of energy from these sources, a backup grid connection ensures uninterrupted power to the hub. While the charging facilities at WattHub primarily support the electrification of construction equipment for the dike reinforcement project, external parties can also utilize the facility.

The main goal of this research is to analyse the operational efficiency and energy sustainability of Mekante Diek's zero-emission (ZE) equipment in combination with WattHub's charging hub. Additionally, this study explores the various factors that influence the performance of charging ZE equipment at WattHub. The findings presented in this report are primarily derived from real-world data collected throughout the project.
The study is a collaboration between TNO and Mekante Diek, supported by a grant from the Netherlands Enterprise Agency (RVO) under the Clean and Emission-Free Construction Equipment Innovation Subsidy Scheme (SSEB Innovation).

The study concludes that the ZE equipment used in the Mekante Diek project, charged at WattHub, offers significant energy savings and emissions reductions. With the combination of renewable energy, innovative charging infrastructure, and sustainable machinery it is shown that large-scale construction projects are possible with ZE-equipment in a sustainable way. Nevertheless, there are opportunities for improving charging efficiency. Optimizing charging schedules, expanding storage capabilities, and refining the energy reservation system may enhance the performance of the charging hub and maximize the use of renewable energy.

<u>Key findings</u>
Energy Consumption of ZE Equipment: Data was collected on the energy consumption of various ZE equipment used in the project, including excavators, tractors, trucks, and cranes. Data collection is an extensive process, influenced by the variety of machines and brands involved, each requiring different methods of data gathering.. The study found significant variability in energy usage depending on the type of equipment and its workload. For example, excavators consume between 50-85 kWh per hour, while tractors use between 12.5 and 31 kWh per hour.

The study also found that the energy consumption by trucks is between 1.8 and 2.4 kWh per km, with trucks used for battery transport consuming slightly more energy. It is recommended to monitor energy consumption more extensively and link this consumption to activities. This can help to predict energy usage for the upcoming periods.

Charging Infrastructure at WattHub: WattHub has proven to be an effective charging location for trucks, construction equipment, and exchangeable batteries. It meets its design objectives by offering a seamless setup, allowing batteries to be safely placed next to chargers without requiring complex manoeuvres or additional security measures for overnight storage. The current energy contracts and infrastructure reliably supply sufficient energy for the Mekante Diek project. Notably, 90% of WattHub's power is sourced directly from the wind farm, while the remaining 10% comes from the grid. With only 15% of the available wind energy utilized so far, there is significant potential for growth and expansion. However, some inefficiencies in the charging process have been identified. Charging sessions are often not optimally utilized, with session times accounting for up to 30% of utilization, while actual charging time is only 13%. This highlights opportunities to improve the efficiency of the charging process. Proposed strategies include scheduled power balancing and slow charging, where the charging power is adjusted based on the expected end time of the session. This approach would take advantage of the longer connection durations

Mekante Diek charging characteristics at WattHub: WattHub serves a diverse range of clients, with the Mekante Diek consortium accounting for approximately 90% of its energy consumption (at the time of this research). The energy demand from the Mekante Diek consortium originates from three main sources for DC charging: Powerboxes (140 kWh batteries), Megaboxes (400 kWh batteries), and trucks (450–540 kWh). In June 2024, Megaboxes constituted 50% of the energy usage, trucks contributed 35%, and the remaining demand was met by Powerboxes. The median charge levels per event were 275 kWh for Megaboxes, 90 kWh for Powerboxes, and 150 kWh for trucks, with higher values typically recorded during overnight charging sessions. The AC-connection is applied for the charging of battery-containers.

Charging behaviour: Charging patterns at WattHub exhibit distinct behaviours across equipment types. Powerbox charging peaks between 11 AM and 4 PM, while Megaboxes display two peak periods in the morning and afternoon. Truck charging is more broadly distributed, with significant activity observed around 4 PM, likely in preparation for the following day’s operations. These patterns reveal notable variability in energy usage, influenced by operational demands. Additionally, the general absence of a base load during nights and weekends highlights an opportunity to implement a more balanced and efficient charging schedule. For instance, advancing the charging of battery containers to earlier time slots could help alleviate morning peak demand and enhance overall energy management.

Energy forecasting: The study emphasizes the significant role of weather prediction in optimizing charging schedules at WattHub. Machines and vehicles may miss opportunities to charge during periods of higher wind energy availability. Incorporating weather forecasting into charging strategies could enhance the utilization of renewable energy, particularly wind power. Devices connected for extended periods, such as those plugged in at the end of the day around 4 PM or on Fridays, are well-suited for delayed charging during times of high wind availability. Short-term weather forecasts (up to four days) can enable more efficient scheduling, allowing these devices to maximize wind power usage and help reduce reliance on grid energy.

Optimize energy consumption at WattHub: The analysis of various charging strategies – via simulation - to optimize energy consumption at WattHub showed that shifting overnight charging sessions to different times can help manage peak loads. However, these strategies did not significantly reduce grid imports or increase wind energy consumption compared to the current approach. Further strategies, such as shifting daytime demand or focusing on night-time charging aligned with wind peaks, may help, but were not simulated. Operational feasibility may limit their implementation. In particular, spreading charging more evenly throughout the night and adjusting charging behaviour based on wind forecasts could reduce grid reliance and optimize the use of renewable energy.

Impact on (avoided) emissions
A major benefit of using ZE equipment is the reduction in emissions. The study compares ZE machinery to conventional diesel equipment across different age categories (old, medium-aged, and modern). The analysis shows that ZE equipment significantly reduces both CO_2 and pollutant emissions (NO_x and PM). For instance, old diesel equipment would emit 12000 kg NO_x and 948 kg PM per year on this construction site, modern diesel powered machinery reduces these emissions to 630 kg of NO_x and 8 to 40 kg of PM. With ZE-equipment these (tailpipe) emissions are completely avoided. Additionally, ZE equipment helps avoid substantial CO_2 emissions (around 940 tons per year).

Contents

1 Introduction

This study concerns a project which focuses on the reinforcement of the dike between Tiel and Waardenburg. The dike reinforcement project aims to enhance the flood protection infrastructure in the region. This initiative is crucial for safeguarding the area against potential flooding threats. The collaborating parties in this project—Ploegam, Dura Vermeer, and Van Oord (collectively known as Mekante Diek)—are committed to executing this project as sustainably as possible. This includes minimizing the use of primary raw materials and maximizing the reuse of materials. In addition, it has been decided to carry out the dike reinforcement project by using zero emission (ZE) machinery as much as possible. It is one of the first large-scale construction projects in the Netherlands to be executed largely with ZE machines and vehicles. This project also focuses on creating a practical, sustainable, and affordable charging infrastructure for construction sites. For this purpose a charging hub is developed by WattHub (collaboration between Van Oord, Ploegam, Dura Vermeer and Betuwe Wind) in Geldermalsen, which is connected to the wind farm of Betuwe Wind and to the grid. Although the charging facilities at WattHub support the electrification of construction equipment of the dike reinforcement project, also external parties can make use of the facility.

The main goal of this research is to analyse the operational efficiency and energy sustainability of Mekante Diek's zero-emission (ZE) equipment in combination with WattHub's charging hub. Additionally, this study explores the various factors that influence the performance of charging ZE equipment at WattHub. The findings presented in this report are primarily derived from real-world data collected throughout the project.

The study is a collaboration between TNO and Mekante Diek, supported by a grant from the Netherlands Enterprise Agency (RVO) under the Clean and Emission-Free Construction Equipment Innovation Subsidy Scheme (SSEB Innovation).

This report presents the monitoring and analysis of real-world data to determine how various factors significantly contribute to the performance of the charging hub and the ZE equipment, and how these factors interact with one another. Four key analyses are conducted in this study:

1. Analysis of energy demand from machinery and vehicles for construction site

In the analysis, several types of machinery (e.g., excavators, loaders, and trucks) are distinguished, as well as different battery types for each type of machinery, where relevant. Furthermore a split is made by types of activities, if possible (e.g., an excavator moving sand versus clay). The significance of these differences will be mapped out, and their impact on predictability will be evaluated. Input for this analysis is provided by Mekante Diek.

2. Analysis of energy supply at the charging station

This analysis examines fluctuations in the daily energy supply, which are expected to vary based on the presence or absence of wind power and the availability of backup from the grid. Input for this analysis is provided by Mekante Diek.

3. Modelling of scenarios
This analysis considers different overnight charging strategies and their impact on the energy mix (wind, solar, or grid) and peak power demand. First, measured data was processed into timeseries production and demand profiles, to represent current operations. Once established, these demand profiles were manipulated with different strategies, such as different night-time delays or limiting peak energy per charger.

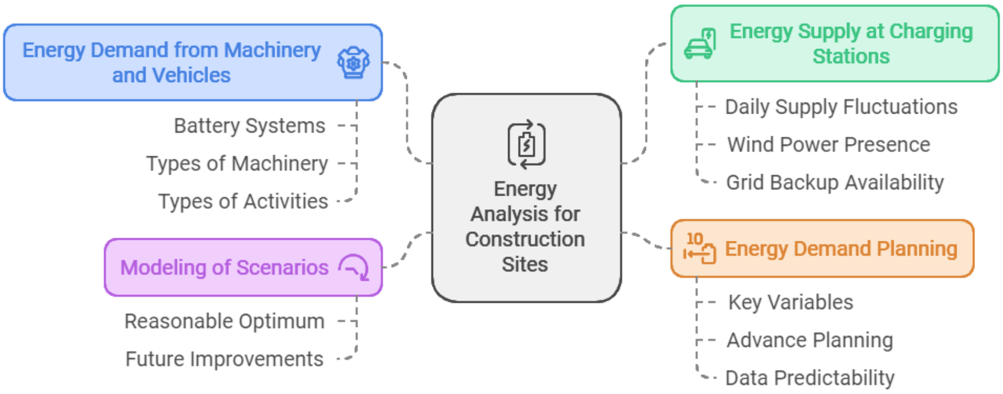


Figure 1.1: Key approach analyses are conducted in this study.

In addition, the possibilities of estimating wind turbine energy production is investigated and the current performance and energy generation is analysed. Finally, the impact on avoided emissions is calculated.

2 Energy demand on construction site

This chapter aims to provide a comprehensive analysis of machinery and vehicles, focusing on their descriptions, working activities, and energy demands. The data gathered for this report is based on different sources, ranging from monitoring data to experiences from the users.

The first paragraph of this chapter details the various types of machinery and vehicles used. The second paragraph highlights the data collection process, emphasizing the practical experience gained during these activities. The third paragraph describes the estimated energy demand per day for each machine and – where possible - activity. It explores the variability in energy consumption, which depends on the type of activity and the specific machine in use. The final paragraph outlines what is possible with current data and identifies the types of data required for accurate energy forecasting.

2.1 Machinery and vehicles used

This paragraph provides an overview of the machines which are active on the dike reinforcement project Tiel-Waardenburg of the consortia Mekante Diek. In Table 2.1 the machines and vehicles their brands and battery capacities are shown, as well as the number of swappable batteries and battery-sharing capabilities. The table highlights the variety of battery configurations in the applied machinery, with a mix of internal and swappable battery systems. Some machines have a significant capacity for energy storage, particularly trucks and large construction machines, while others like rollers and pavers have relatively small capacities. The ability to share batteries across machines provides flexibility for certain machines. This has the advantage of having charged battery boxes 'in stock' for machines that need them.

The table presents a diverse range of machinery, including excavators, tractors, trucks, loaders, wheeled excavators, asphalt pavers, rollers, silent pilers, and cranes, from brands such as Caterpillar, Doosan, Fendt, Volvo, and Giken. Notably, there are some gaps in the data, with missing information for certain machines, those are listed as "n/a," where battery capacities and other details are not provided. Those are machines which are not continuously working on the project and are often sub-contractors.

Battery configurations vary, with machines equipped with internal batteries and swappable batteries. Internal battery capacities range from 30 kWh (for asphalt rollers) to 540 kWh (for Volvo trucks), while swappable batteries are mostly seen in Doosan and Fendt machines, with (total extra) capacities up to 400 kWh. Doosan excavators and Fendt tractors feature two swappable batteries each. Those are extra to the "internal" battery, which is actually swappable as well.

Most Doosan, and Fendt models can share batteries (among machines of the same brand), while Volvo trucks and other machines do not offer this capability.

Larger machines, such as Volvo trucks, have significantly higher internal battery capacities compared to smaller machines like the mini-shovel (40 kWh). Some specialized machines, like the Silent Piler and Wheeled excavator, have a single swappable battery with a capacity of 350 kWh.

Table 2.1: Overview of applied machinery and vehicles at the Mekante Diek project

Machine	Brand	Bruto capacity* internal battery	Bruto capacity swappable batteries	Number of swappable batteries	Battery shared with other machines
[-]	[-]	[kWh]	[kWh]	[Number]	[yes/no]
Excavator	Caterpillar	400	-	-	
Excavator (4x)	Doosan	-	400	2	Yes
Excavator (3x)	Caterpillar	470	-	-	-
Tractor (5x)	Fendt	70	140	1	Yes
Truck 8x4 (7x)	Volvo	540	-	-	-
Loader	Doosan	400	-	-	-
Wheeled excavator (2x)	Doosan	-	400	1	Yes
Truck – battery transport (2x)	Volvo	540	-	-	-
Asphalt Paver	n/a	-	115	4	
Asphalt roller	n/a	110		-	-
Asphalt roller	n/a	-	115	2	
Asphalt roller	n/a	30	-	-	-
Asphalt roller	n/a	75	-	-	-
Truck for road construction	n/a	450	-	-	-
Truck for road construction	n/a		-	-	-
Mini-shovel	n/a	40	-	-	-
Roller	n/a	-	115	2	
Silent Piler	Giken	-	360	1	-
Silent Piler	Giken	-	350	1	-
Crane (2x)	n/a	280	-	-	

* The usable capacity varies per brand.

2.2 Data collection process

Data collection is an extensive process, influenced by the variety of machines and brands involved, which each require different methods of data gathering. Not all machines provide online telemetry data, and this poses challenges in some cases. For example, machines such as asphalt equipment which are operated by subcontractors make data collection even more difficult.

For machines and vehicles used on a fixed basis on the Mekante Diek project, the data collection methods vary by brand. Caterpillar excavators have an online export tool that allows for energy usage to be downloaded per minute for each machine. The Doosan machines are in the process of having a dashboard developed, but for now, operators manually track energy consumption. Fendt tractors had their charging energy monitored by operators over a certain period. Volvo trucks offer an online dashboard.

The working activities are not consistently monitored, with data collected only during specific periods.

For a more detailed energy consumption profile, it is recommended to gather data at intervals of every second or minute. Ideally, a real-time dashboard would provide the most efficient and accurate data collection method.

The data on energy usage was gathered by Mekante Diek, and sent to TNO. For most of the equipment the level of detail was limited. TNO has no sight on the validity for most of the collected data.

2.3 Estimated energy demand per day for each machine

This paragraph provides detailed information on the energy consumption of various machines and vehicles under different workload conditions, including light, medium, and heavy work. The workload conditions are based on the activities and their energy usage. The energy consumption is given in kilowatt-hours per hour (kWh/h) or kilowatt-hours per kilometre (kWh/km), depending on the machine type. As mentioned in the previous paragraph the energy consumption data was gathered by Mekante Diek, based on different sources. The daily deployment (in hours) was roughly estimated. Based on the estimated deployment per day, in combination with the energy consumption per hour, the total energy usage per day (in kWh) is calculated. Table 2.2 provides an overview of the results.

For the Caterpillar excavators, energy consumption ranges from 48 kWh/h for light work to 85 kWh/h for heavy work, with an estimated average deployment of 8 hours per day. Based on the medium workload, this results in a daily energy consumption that ranges from 384 kWh to 680 kWh, depending on the workload. The Doosan Excavators exhibit a comparable energy consumption, ranging from 55 kWh/h to 80 kWh/h, also with an 8-hour daily deployment, resulting in a daily energy usage between 440 and 640 kWh.

The Fendt Tractors consume 12.5 kWh/h during light work and 31 kWh/h during heavy work. With a daily deployment of 8 hours, these tractors use 100 to 248 kWh per day.

For Volvo Trucks (8x4), energy consumption is measured per kilometre and ranges from 1.8 kWh/km for light work to 2.4 kWh/km for heavy work. With an estimated daily deployment of 100 kilometres, the trucks consume 180 to 240 kWh per day.

For the Doosan Loader there is a lack of data for this particular machine.

The Doosan wheeled excavators consume between 27 kWh/h for light work and 33 kWh/h for heavy work, and with 8 hours of daily operation, their total energy usage is between 216 and 264 kWh per day.

For Volvo Trucks used for battery transport, the energy consumption is somewhat higher, ranging from 1.8 kWh/km for light work to 2.9 kWh/km for heavy work. With a deployment of 105 to 120 kilometres per day, these trucks require approximately 190- 350 kWh daily.

The energy consumption of the asphalt set is still unknown.

The Giken Silent Pilers consume 50 kWh/h during light work and 87.5 kWh/h during heavy work. Finally, Cranes show an energy consumption of around 19 kWh/h during medium work.

This data highlights the varying energy requirements across different types of machines and workloads, with excavators, trucks, and silent pilers generally consuming more energy, particularly during heavy operations. The table also underscores the importance of knowing the impact of work intensity and daily deployment on total energy usage.

Most of the machines from this table are operating every day, except for the asphalt set.

Table 2.2: Energy consumption and deployment per machine/vehicle.

Machine/vehicle	Brand	Unit	Range in energy consumption (light to heavy work)	Assumed deployment per day [h or km]	Energy per day [kWh]
Excavator	Caterpillar	kWh/h	48 - 67	8	384 - 536
Excavator (3x)	Doosan		55-80	8	440 -640
Excavator (3x)	Caterpillar		57-85	8	456 - 680
Excavator	Doosan		60-80	8	480 - 640
Tractor (5x)	Fendt	kWh/h	12,5 – 31	8	100 - 248
Truck 8x4 (7x)	Volvo	kWh/km	1,8 – 2,4	100	180 – 240
Loader (4x)	Doosan	kWh/h	-	-	-
Wheeled excavator (2x)	Doosan	kWh/h	27 – 33	8	216 - 264
Truck – battery transport (2x)	Volvo	kWh/km	1,8 – 2,9	105 - 120	189 - 348
Total asphalt set	-	kWh/h	-	-	-
Silent Piler (2x)	Giken	kWh/h	50 - 88	-	260*
Crane (2x)			**19**	**-**	

* Based on 1300 kWh per week for the four machines combined.

3 Batteries in the Mekante Diek project

Battery swapping is integral to the ZE equipment operation. Two trucks as well as one tractor are utilized for battery transport. All vehicles were fully electric. One truck is transporting the swappable batteries, while the other truck and the tractor transport the battery container. The process of battery swapping was not monitored in a quantitative way in this study. Information on battery swapping is gathered via a physical visit. One of the three vehicles responsible for transporting batteries was accompanied during one working day. It concerns the truck which transport the swappable batteries. With an empty mass of 28 tons, the maximum load is 22 tons. This truck can load (via an electric crane) up to a maximum of seven swappable batteries. The other two vehicles only transport large battery containers. One of these is a truck, and the other is a tractor, which allows access to difficult locations. Each trailer can carry one battery container. There are five battery containers in total, distributed between the two vehicles. Drivers often have to wait at charging stations for batteries to fully charge.

<u>Transport Process</u>
Battery transportation begins early in the day, with the driver starting at 5:00 AM and finishing between 5:00 and 5:30 PM. At present, one truck is sufficient for transporting the swappable batteries. The truck itself has a 540 kWh battery, and the crane mounted on the truck, used for lifting batteries, is also electric and has a 60 kWh battery pack. The truck's normal range is 300 km, but due to frequent use of secondary roads, this range is often not achieved. For instance, during the visit, the current battery level was at 75%, but the estimated range was only 171 km. This range further decreases during winter. Regenerative braking could help extend this range. The truck is recharged during the day at WattHub, usually during breaks, such as lunchtime, ensuring enough energy for the entire day.

<u>Work Process</u>
The driver places the batteries into the machine, while the operator connects and disconnects the electrical components. In most cases, the number of batteries brought matches the number being taken back. There is no fixed schedule from the office, and operators communicate directly with the driver, typically half a day to a day in advance, making the operator responsible for coordination. At some sites, batteries are regularly swapped every morning due to repetitive tasks, while at other locations, this varies daily.

Battery swaps are not only performed when they are depleted but also when it's convenient based on the route. Clear communication between the operator and the driver is essential for smooth operations. Regular operators are the most comfortable with this process, as they are familiar with both the machine and the behaviour of the batteries. For machines like crawler cranes, driving consumes significant energy and time, so batteries should be placed as close to the construction activity as possible.

<u>Multiple Battery Swap Locations</u>
At Ophemert/Varik, batteries are swapped daily in the morning and evening for three machines.
The entire swapping process takes about an hour, with two batteries per machine, totalling six batteries. Since there are two batteries per machine, swaps can be done efficiently rather than waiting for full depletion. Batteries are not always completely drained before being swapped and recharged daily.

At Zennenwijnen/Tiel, there are two crawler cranes and one wheeled excavator, with one having a fixed battery. The wheeled excavator can operate for 12 hours, and battery swaps are done on an ad-hoc basis, with no fixed routine.

At Waardenburg/Ophemert, similar processes are followed.

<u>Battery Swapping and Charging</u>
Swapping two batteries for a machine typically takes about 15–20 minutes, with setting up the truck's stabilizers being the most time-consuming part. For tractor batteries, the process is faster, around 10 minutes. If a machine with a fixed battery needs to be recharged mid-operation, this takes about an hour. Operators generally prefer swapping batteries, as it is almost as fast as refuelling with diesel, although refuelling with diesel is not needed every day. Crawler cranes can usually operate for 8 hours with two swappable batteries, while wheeled excavators only require one.

There are some excavators that need to recharge twice a day, as their 400 kWh battery pack is insufficient for full operation, making battery swapping a more convenient option. Swappable batteries are compatible across different machines of the same brand, and batteries picked up in the morning are often used by other machines by the afternoon.

In some locations, excessive soil or lack of grip can pose challenges, especially for fully loaded trucks. In these cases, steel plates are required for stability. Swapping batteries is ideally done at fixed locations where trucks can easily access the site.

There are a few machines with non-standard battery packs, which do not have additional batteries. This makes transportation less efficient, as the same number of batteries cannot be returned as were delivered. Adding an extra battery would be significantly more expensive than the necessary transport costs. Therefore, for these machines the batteries need to be charged when they are not deployed.

The truck aims to drive as fully loaded as possible, but this is not always achievable. It usually works out at the beginning and end of the day during the fixed rounds. Ideally, charging should occur after 10:00 AM due to lower energy costs, when wind and solar power are more readily available.

More detailed data on battery swapping processes, such as transport distance and turnaround time, would help optimize this system. Moreover, it is recommended to analyse the transport of the battery-containers in more detail as well.

4 The charging hub WattHub

This chapter provides a detailed analysis of the charging hub, focusing on its electrical setup, power demand, and equipment charging behaviour, based on technical schematics, energy consumption data, and user activity at WattHub.

The first section introduces the schematic of the electrical connections, detailing the grouping and distribution of chargers across the hub. The second section examines the hub's power demand, using charging events from the Mekante Diek consortium and other users. Finally, the chapter explores equipment charging patterns, analysing typical charging times and average energy usage.

Due to data limitations, such as the lack of links between battery identification and specific machines or their work, this analysis focuses solely on charging events rather than machine operations.

The chapter concludes with an evaluation of current charging patterns, identifying trends and potential areas for optimization, which lay the groundwork for future improvements in energy management at the hub.

4.1 WattHub electric connections

WattHub aims to operate exclusively on wind energy, supporting its mission of emission-free construction. To achieve this, the charging schedule is optimized to align with periods of peak wind energy availability. Additionally, WattHub plans to connect indirectly to a local solar energy farm, further enhancing its reliance on renewable energy sources.

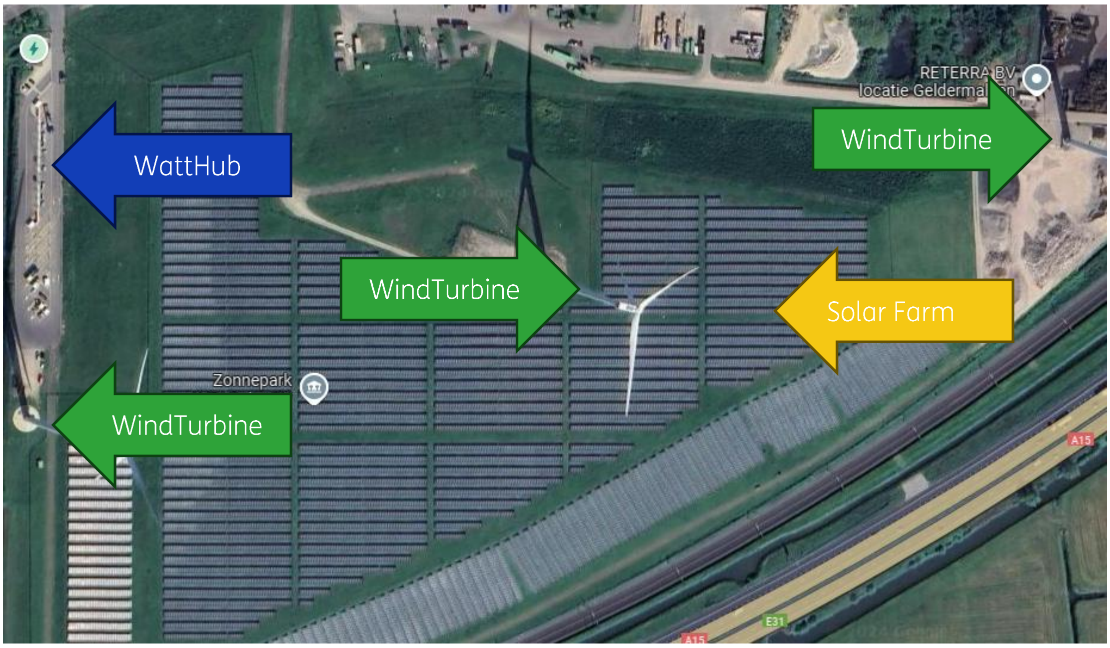


Figure 4.1: Location of WattHub, Wind Park, and Solar Park on the Map. Source Google Maps.

WattHub is directly connected to three wind turbines from the Avri wind power station operated by Betuwewind, located just a few meters away, as shown in These connections enable the chargers to draw power directly from the wind turbines via two transformers: a 2.2 MVA[1] unit for the Kempower system (DC charging with the CCS standard) and a 1 MVA unit for Power Lock connections (AC connections for container batteries using Power Lock connectors).

During periods of low wind speeds, WattHub relies on a backup grid connection with a capacity of 10 MVA. In the summer, this connection provides 2.3 MVA of contracted energy, while in the winter, it is only available during night-time operations. At the time of writing, new contract conditions were under negotiation, potentially allowing for increased capacity or more flexible usage.

The connections at WattHub are illustrated in two figures. Figure 4.2 depicts the interconnection between WattHub, the electrical grid, and the wind turbines, including the placement of primary and secondary meters. Complementing this, Figure 4.3 outlines WattHub's internal electrical setup, showing the relationships between the main supply, transformers, and charger groupings. Together, these figures provide a comprehensive view of WattHub's power infrastructure.

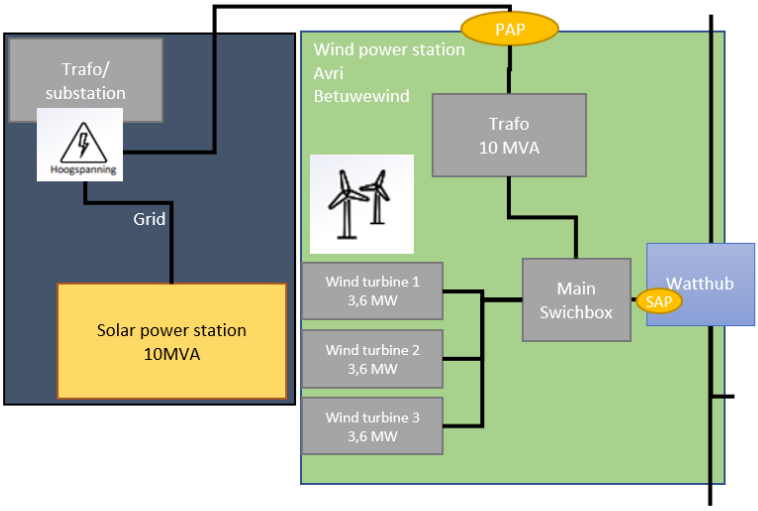


Figure 4.2: WattHub power connection.

[1] Apparent power "S" (in VA) in AC systems represents the total power, including both real power "P" (in kW), which does useful work, and reactive power. The real power is calculated as P = S * cosϕ, where cosϕ is the power factor. In DC systems, only real power is considered

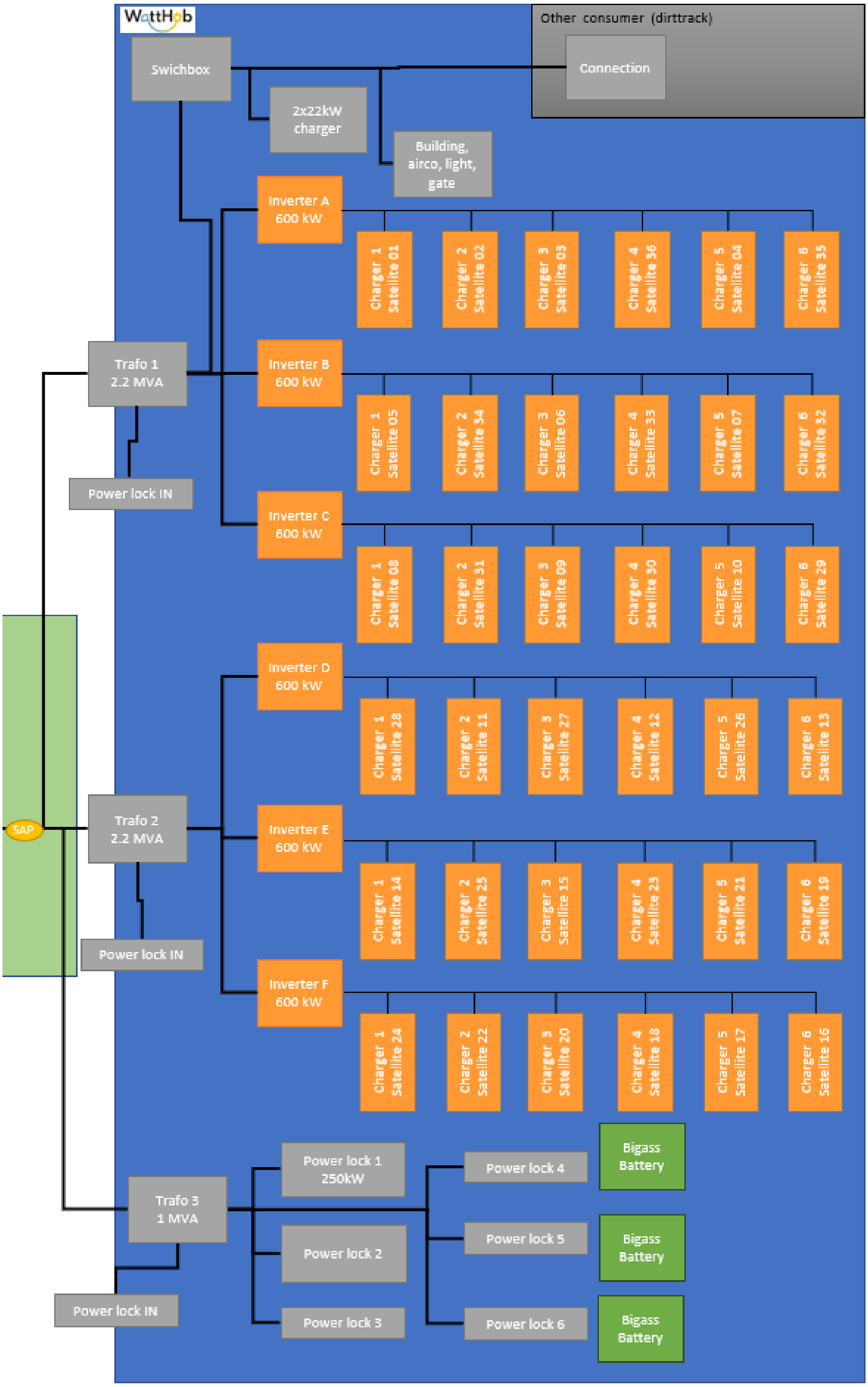


Figure 4.3: WattHub Internal power distribution and charger connections.

For DC charging, WattHub has 36 Kempower[2] smart charging stations (Satellites) equipped with CCS connectors capable of 400 kW. Additionally, it is equipped with 6 AC connections that use power lock connectors and are capable of charging container batteries (that use power lock connectors) with a power per connection of up to 250 kW. The 36 satellite chargers are connected and controlled in groups of six and provide between 25 and 400 kW. The group (6 chargers) is connected via an inverter station that can provide up to 600kW.

As an example for overnight charging, the power of the inverter station can be equally distributed among the 6 satellites for slow charging (100kW per charger). During the day the power of the inverter station can be concentrated to two chargers and provide 300 kW for each charger or prioritise one with 400 kW and provide 200 kW to the other. Other combinations are possible depending on connected vehicles/batteries and the system settings. The image below from the Kempower website shows an example of power distribution in a similar system (see Figure 4.4).

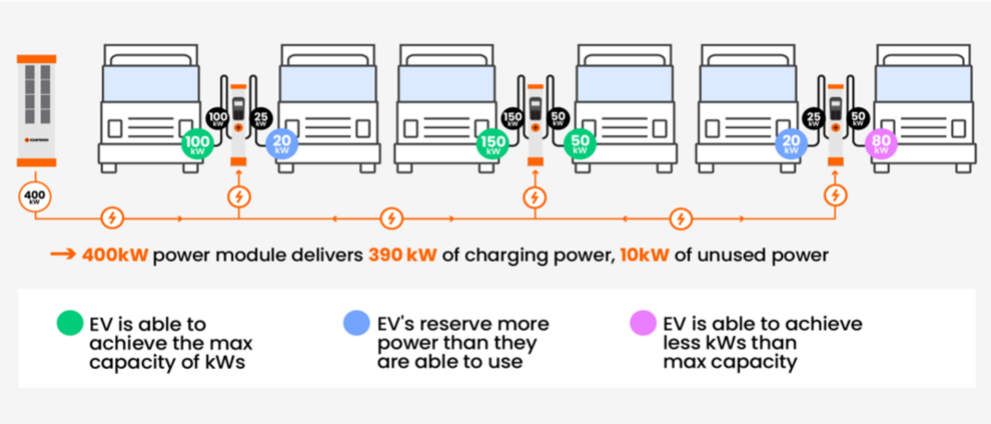


Figure 4.4: Example of possible dynamic power sharing on Kempower satellite system. (Source: Kempower)

4.2 Spatial distribution of the charger.

WattHub is a semi-public facility with controlled access through a gated entrance. Only authorized individuals or registered WattHub customers can access the charging hub after registering via intercom. This controlled access ensures the secure charging and storage of movable batteries used in construction equipment.

Figure 4.5 illustrates the design concept of the hub, showcasing its layout and key features, such as designated charging zones and access control mechanisms. This design reflects WattHub's focus on safety, efficiency, and adaptability to diverse charging needs.

[2] World's first fast-charging plaza for trucks & heavy construction equipment - Kempower

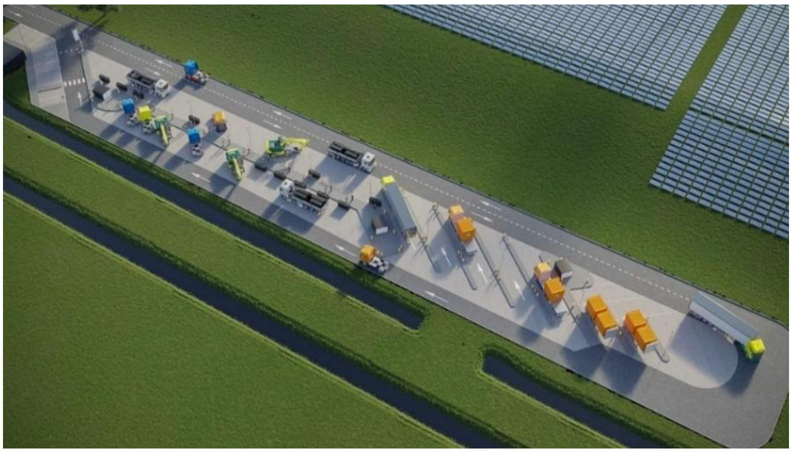


Figure 4.5: WattHub designed image (Source: WattHub)

The hub is organized into three semi-dedicated areas, each serving a specific purpose (as shown in Figure 4.6):

- Primary battery and equipment charging area (orange): Designated for charging movable batteries and equipment used in construction.
- Primary truck charging area (blue): Allocated for charging trucks and other heavy vehicles.
- Container battery charging area (purple): Equipped with AC power lock connections for charging container batteries.

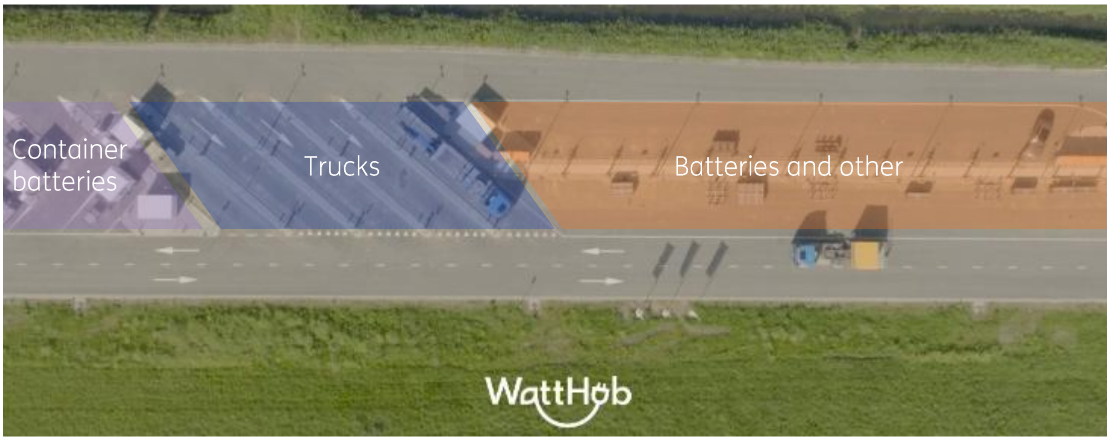


Figure 4.6: WattHub chargers spatial distribution with the marking of are for dedicated usage. Orange – Battery and equipment, Blue- Trucks, Lavender -Container batteries (Picture source WattHub)

The dedicated battery charging area is in the form of a parallel parking area, allowing easy loading and unloading of batteries from the trailer. The picture below shows a truck preparing to unload empty batteries and pick up fully charged batteries.

Figure 4.7: Truck exchanging the empty batteries for full at the battery charging area of WattHub (Picture source WattHub).

The truck charging bay is designed as a drive-through, allowing a tractor with a trailer to easily approach the charger without having to reverse or uncouple the trailer. Multiple charging points in the drive-through bays also allow two rigid trucks to be charged in one bay at the same time.

Figure 4.8: Track parking and truck charging in the drive-through area (Picture source WattHub).

The container battery charging area is designed to allow the container battery to be parked on a trailer close to the power lock connection point and easily connected.

Figure 4.9: The container battery charging in the container charging area of WattHub. Connected to the AC charging (power lock) installation.

However, there are limitations. Grouping the chargers and connecting six 400kW chargers (satellites) to one 600kW inverter station creates restrictions when many vehicles are connected to a group. This is most noticeable for vehicles that require immediate and fast charging, especially in the truck charging area where two inverters supply power to the charging points. This means that if more than two trucks are charging at the same time and require more than 400kW of combined power, the power distribution will limit the charging power.

4.3 Energy delivered (charging demand)

The WattHub started its operation in the summer of 2023, therefore the data available is limited and includes the startup period. The data from the Kempower System came from the charger and shown how much energy was charged to the devices during a period of 1 year (from 1 June 2023 to 30 June 2024.). For the power locks in mid-January 2024 meters were installed and the energy charged via the power locks installation was measured. The data delivered from the power lock measurement available for the period from 1st February to 30th June 2024. The analysis of the data from the Kempower system and the power locks is showing an increasing trend in energy usage.

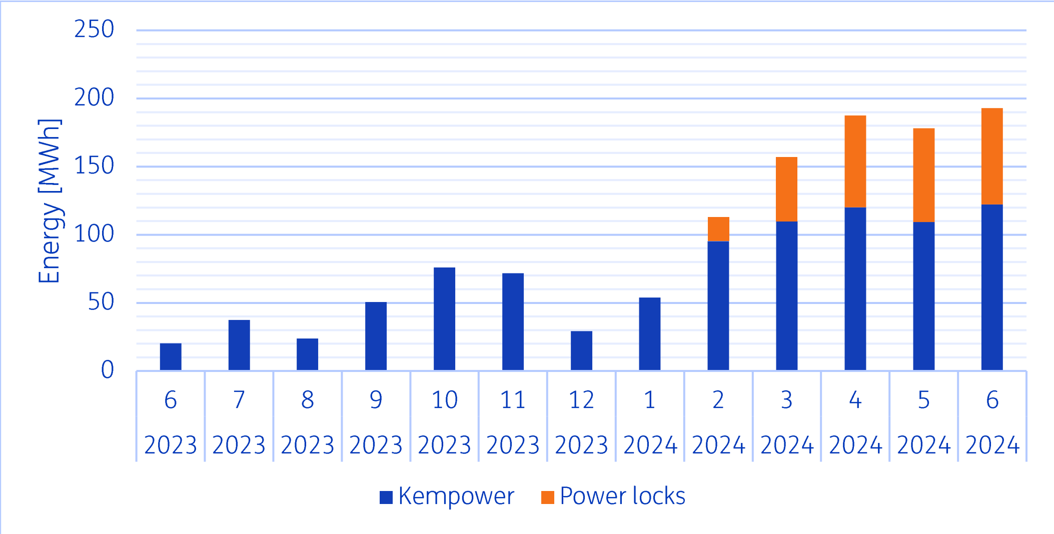


Figure 4.10: WattHub energy used during the monitoring period.

The energy deliver by the DC charging system increased by 100 MWh between June 2023 and June 2024, reaching approximately 120 MWh. The average energy delivered on the power locks from April to June 2024 was around 65 MWh .

The overall trend is upward. Additionally, the influence of holidays in August and December/January is evident as a decrease in utilisation. By contrast, high session times are observed in February, April, and March 2024, indicating peak activity during these months.

It is important to note that the data represents only one year of operation for a single project, and may not be fully representative of broader industry trends. The Mekante Diek team mentioned that the charging behaviour is expected to differ in 2024, as the work is heavily influenced by weather conditions and, in the case of dike reinforcement, water levels.

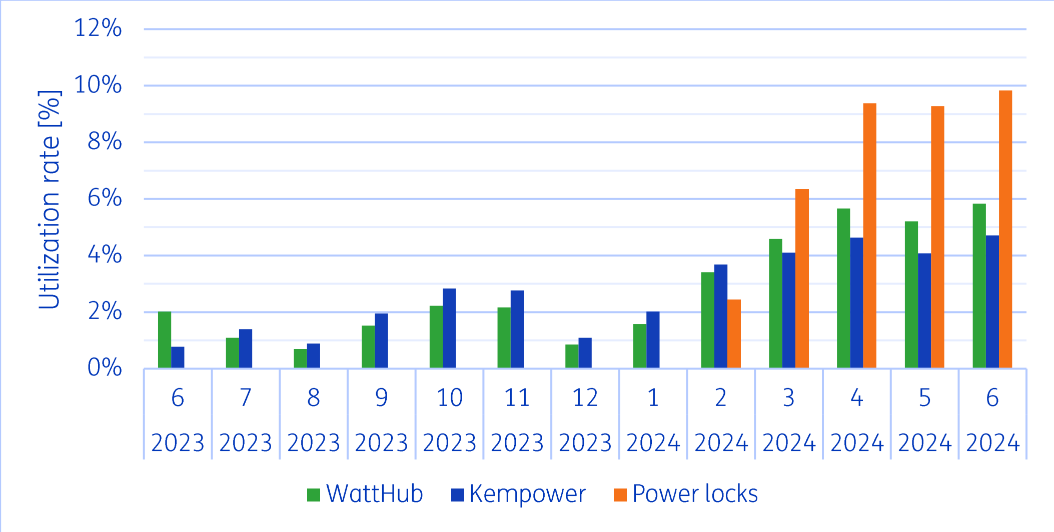


Figure 4.11: WattHub utilization rate with utilization of the DC charging infrastructure (Kempower system) and the AC charging (power locks) For the utilization calculation: it was considered that each inverter group can provide a maximum of 600 kW. The power locks can be only used simultaneously with a restriction of the power taken by all of them to 1 MWh. Data for power locks are only available from February. The utilization is calculated based on the hub operating 24 hours a day, every day of the month.

Charging data from the Kempower system shows the difference between charging time and session time (vehicle connection to the charger). Based on the hub's 24-hour operation, charger utilization over time was calculated (the percentage of time the charger is in use during a 24-hour period). Analysis of the utilization data reveals that session time exceeds 30%, while actual charging time accounts for only 13%. This indicates a significant discrepancy between the time a vehicle is connected to the charger and the time it is actually charging, suggesting potential inefficiencies or areas for optimization, such as reducing charging power or optimizing charging time start.

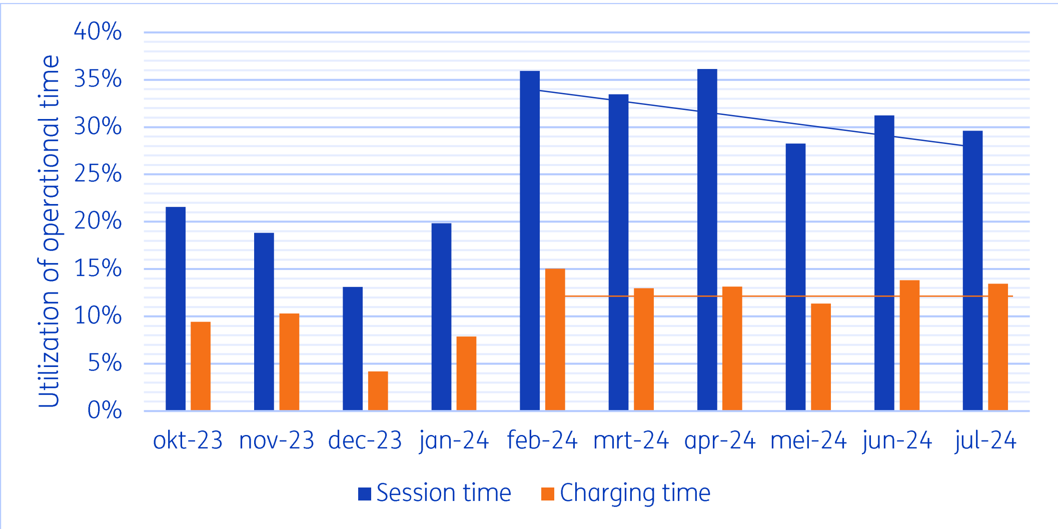


Figure 4.12: WattHub DC charging infrastructure utilization rate in time for the session (connection to the charger)and charging time. Operational time of WattHub 24 hours a day 7 days a week.

4.3.1 Mekante Diek charging patterns at WattHub

The analysis of charging patterns at WattHub for this study focused on the Mekante Diek consortium and the equipment used in the dike reinforcement project.

Therefore, energy demand at WattHub is divided into two segments:

- The Mekante Diek project: Covering all energy demands related to the dike reinforcement equipment.
- Other users: Encompassing all other companies and individuals utilizing WattHub for charging.

Dividing the energy demand from the Mekante Diek consortium into 3 main groups related:

1. the batteries ECE_140 – Powerbox (Powerbox140) - Battery size of 140 kWh
2. the batteries ECE_385 -Megabox (Powerbox400) – Battery size of 400 kW
3. The trucks with battery size of 450 and 540kWh

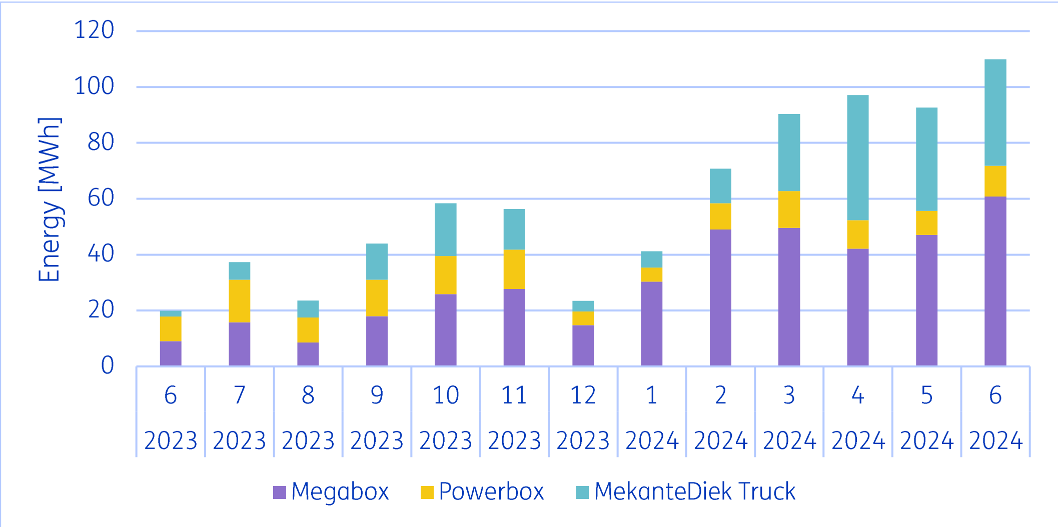


Figure 4.13: The energy consumption at WattHub across three equipment categories—Megabox, Powerbox, and Mekante Diek Trucks—from June 2023 to June 2024.

Megaboxes have consistently high energy consumption each month reaching 60 MWh in June 2024, they contribute to a steady demand for energy at the charging hub.
The Powerboxes have lower energy usage of 11 MWh in June 2024.

Mekante Diek Trucks show increasing energy consumption over time, particularly in 2024. This is due to more intensive usage by the 10 trucks. In June 2024, the 10 trucks consumed 38MWh which is 35% of the energy charge at WattHub, while the 20 Megaboxes consumed 50% of the energy.

In summary, the Megaboxes provide a big demand due to their utilization and high total capacity spread across many units. Powerboxes provide lower energy demand at the WattHub. The Mekante Diek Trucks, with their intensive usage, account for the second largest and steadily growing portion of energy consumption, especially as project activities have increased.

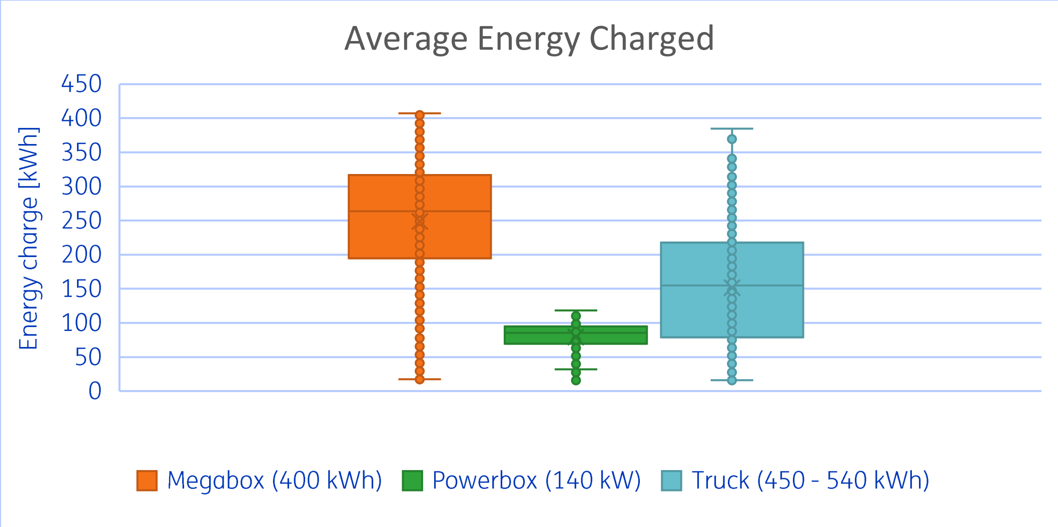


Figure 4.14: Distribution of energy charged per event for Megabox, Powerbox, and Trucks.

The Megabox median charge level is around 275 kWh, suggesting that this is a "typical" consumption/discharge level for Megaboxes, and 50% of charging events fall within the range of 200–330 kWh.

The Powerbox's median charge level is 90 kWh, close to the upper quartile at 100 kWh. This aligns well with its smaller capacity and lower variability, with most sessions falling between 60–100 kWh.

Trucks exhibit the most variability in charging levels, reflecting different usage patterns and variability in battery capacities (450 and 540 kWh options). The median for trucks is at 151kW with 50% of all recorded charging events falling between 80 to 217 kW.

When analysing charging patterns based on the time of connection, distinct behaviours emerge for Powerboxes (see Figure 4.15), Megaboxes (see Figure 4.16), and Trucks (see Figure 4.17).

The daily operational cycle at the hub begins between 6 and 7 a.m., with work concluding around 4 p.m. when most trucks return to the hub with the last battery load. Although all devices are typically connected by this time, some charging events are deferred until later in the evening to align with operational priorities and energy availability.

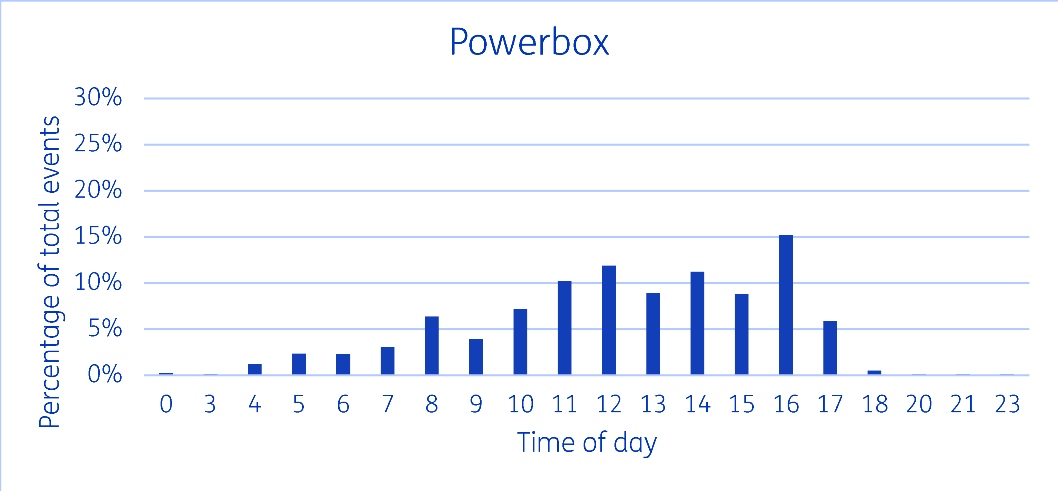


Figure 4.15: Distribution of charging events throughout the day for Powerboxes. This figure illustrates the frequency of charging events starts initiated throughout the day for the Powerboxes. The graph highlights the times of day when charging activities peak, indicating usage patterns.

Powerboxes are most frequently connected to chargers between 11 a.m. and 4 p.m., with the highest activity occurring around 4 p.m., aligning with the routine delivery of empty batteries for charging. Typically, batches intended for overnight charging are delivered at the end of the workday. Early morning charging events between 5 a.m. and 7 a.m. indicate reconnections of Powerboxes that were not charged overnight, possibly due to energy shortages or technical issues.

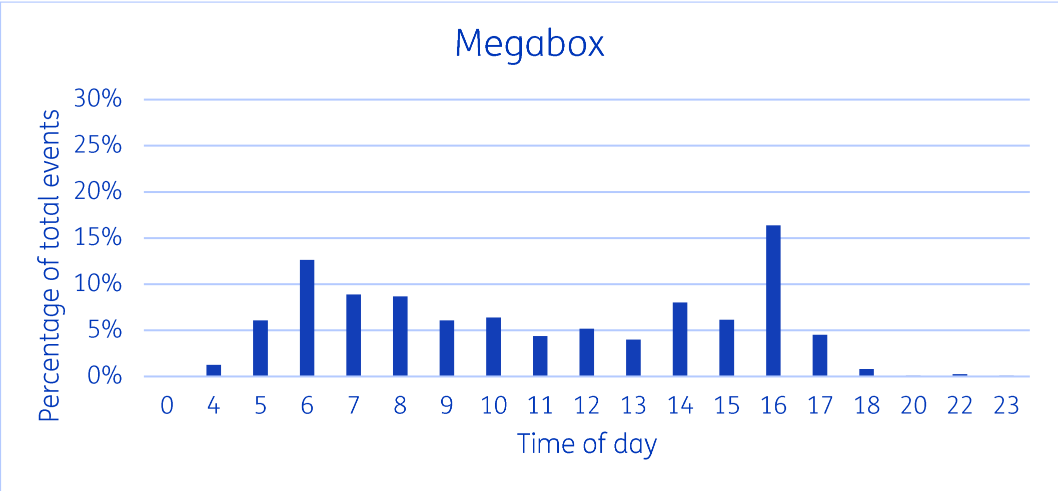


Figure 4.16: Distribution of charging events throughout the day for Megaboxes. This figure illustrates the frequency of charging events starts initiated throughout the day for the Megaboxes. The graph highlights the times of day when charging activities peak, indicating patterns of usage and demand.

Megaboxes exhibit two distinct connection peaks: an early morning peak around 6 a.m. and a higher afternoon peak near 4 p.m. These patterns align with worksite operations.
The morning peak reflects the restarting of charging for batteries left uncharged overnight, while the afternoon peak indicates that most batteries are utilized throughout the full workday, necessitating recharging upon their return.

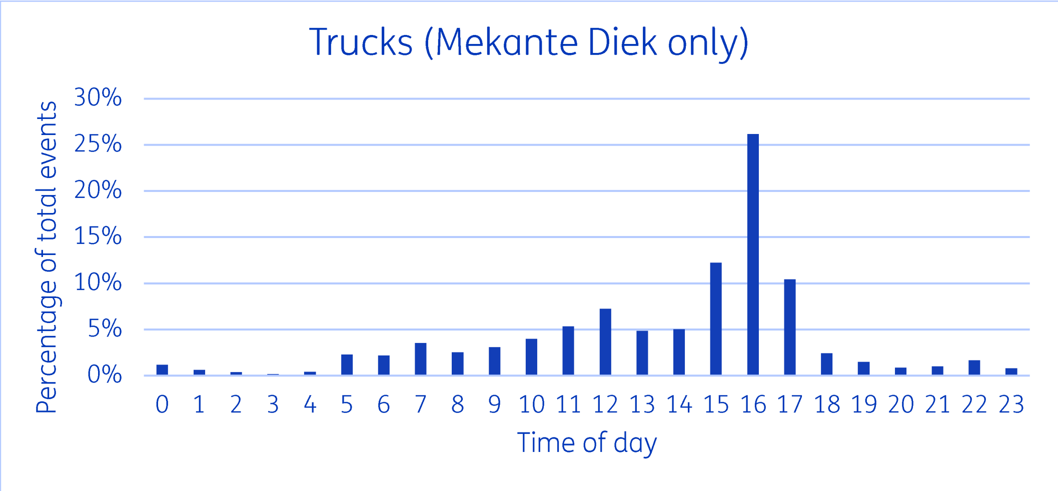


Figure 4.17: Distribution of charging events throughout the day for Trucks. This figure illustrates the frequency of charging events starts initiated throughout the day for the Trucks. The graph highlights the times of day when charging activities peak, indicating patterns of usage and demand.

Truck connection patterns show a broader distribution throughout the day, with a notable peak around 4 p.m. Trucks, equipped with large battery capacities (450–540 kWh), follow a two-round operational schedule: in the morning, charged batteries are swapped for depleted ones from the worksite, and this process repeats after lunch. The late afternoon peak reflects preparations for the next workday, while early morning charging events suggest restarts or connections of trucks that were not fully charged overnight. These patterns highlight the operational rhythm and its influence on energy demand at WattHub.

An examination of WattHub's energy consumption throughout the day (see Figure 4.18) reveals no consistent base load to the network. Energy usage is highly variable, frequently dropping to zero, particularly at night and on weekends. Demand increases noticeably in the morning and afternoon, peaking when both AC and DC charging installations are in use simultaneously. To alleviate the morning peak, adjusting the Power Locks to begin operations around 1 a.m. could help distribute energy demand more evenly and improve overall efficiency.

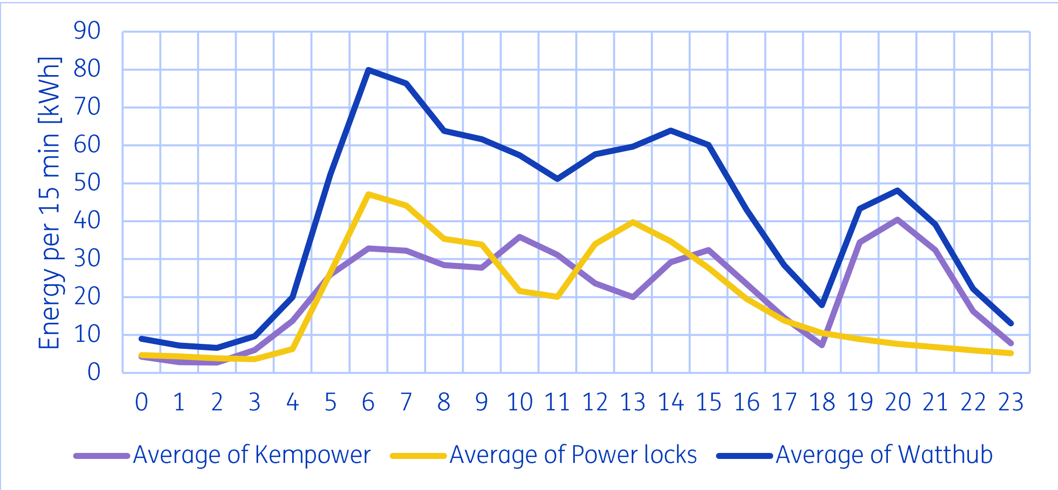


Figure 4.18: Average energy consumption per 15 min by the Kempower, power locks and the WattHub (Kempower+power locks) on an average workday.

When focusing on WattHub's energy consumption (Kempower and power locks), as shown in Figure 4.19), peak power consumption reaches around 300 kWh (1200 kW) in the morning. An analysis of the standard deviation in the data reveals minimal activity at night, but significant variability during the day. This deviation, almost equal to the average daytime energy consumption, reflects intermittent high-demand charging events driven by operational needs. The pronounced variability highlights the importance of strategies for smoothing energy demand, such as load balancing or scheduling charging events to reduce peak loads and enhance system efficiency.

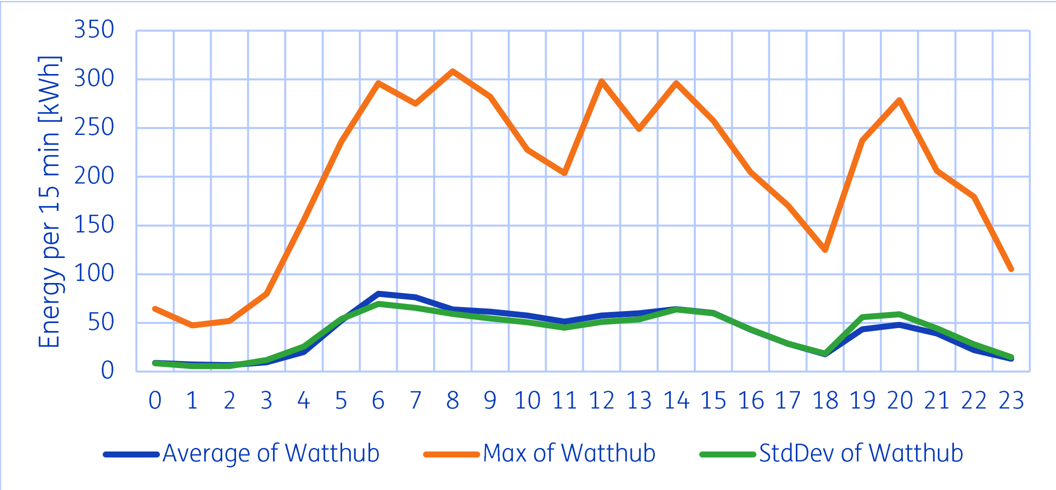


Figure 4.19: Average, maximal and standard deviation of energy consumption per 15 min by WattHub on an average work day.

Figure 4.20, illustrates the energy charged per day across multiple months, with June 2024 representing the period of highest energy usage observed to date. During this month, the average daily energy charged was approximately 4.5 MWh, with a maximum of nearly 7 MWh recorded. In other months, such as May and April 2024, higher daily peaks of up to 7.5 MWh were observed. The variability in daily energy usage remains significant, driven by project phases, machinery usage, and other operational factors.

Over the full year (June 2023 to June 2024), the average energy charged per day is slightly lower, reflecting the initial startup phase with reduced equipment availability. These fluctuations underscore the need for flexible energy procurement and planning to accommodate changing project demands.

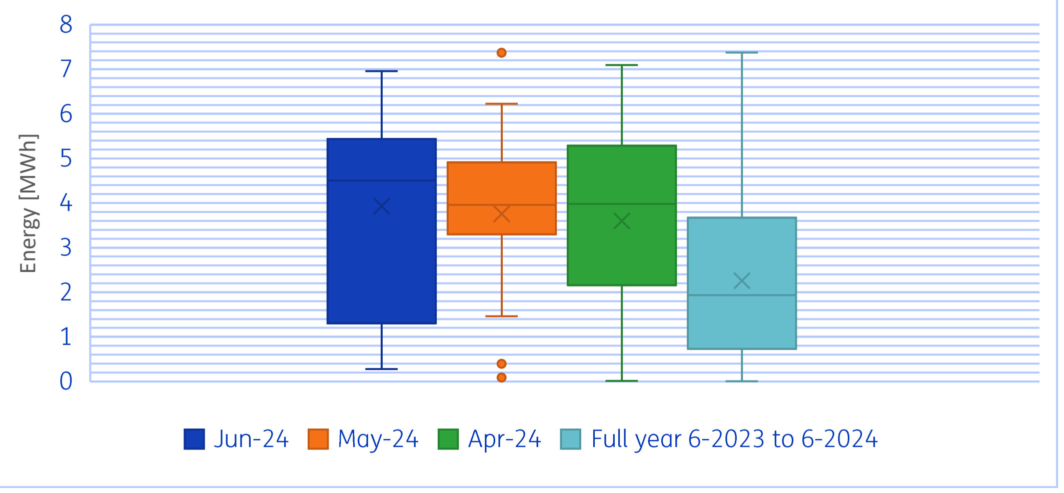


Figure 4.20: Energy charged on average per working day by Mekante Diek consortium at WattHub

4.4 Energy Mix Utilization at WattHub

The primary objective of the WattHub is to maximize the use of renewable energy generated by the wind farm. Figure 4.21 shows the proportion of energy sources used by the hub during the period from May to September.

The data indicates that, on average, 89% of the energy was derived from the wind farm, with only 11% drawn from the grid. This result was made possible due to the wind farm's significant overcapacity relative to WattHub's energy demand.

Discussions with WattHub revealed that there were occasions when equipment could not be charged due to a lack of wind. This report does not analyse these instances, as the relevant data is unavailable. However, it is anticipated that, as energy demand at WattHub grows, maintaining such a low dependency on grid energy will become more challenging.

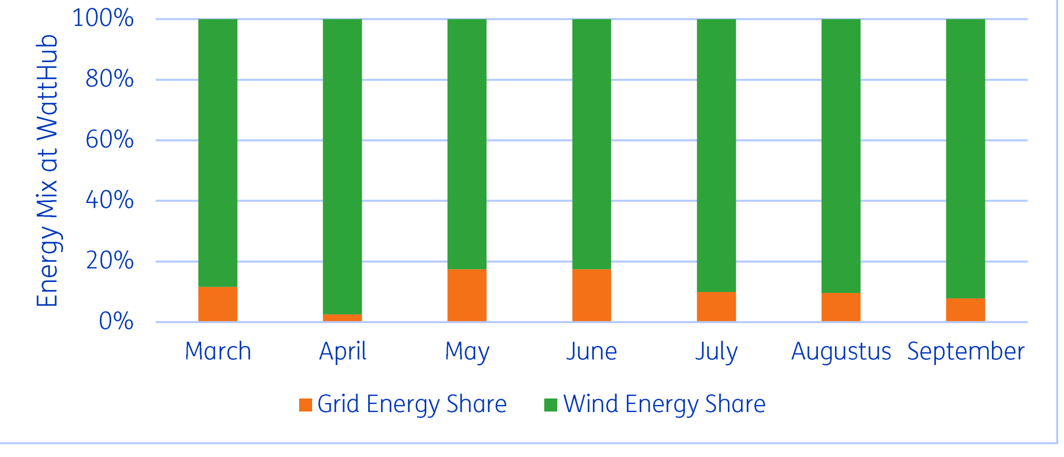


Figure 4.21: Share of grid and wind energy consumed by WattHub.

This shows that the wind farm is the main source of energy used at WattHub. The hub is located next to a solar farm, so physically, the energy from the grid during daytime and the summer months would likely come from the solar farm. It is worth mentioning that, from September 2024, WattHub has a contract with the solar farm to purchase energy via their grid connection.

Looking at the energy produced by the wind farm and consumed by WattHub, an average of 10% of the total energy produced by the wind farm was consumed by WattHub during the above period. This proportion shows that there is room for growth and as mentioned optimization of the energy consumed.

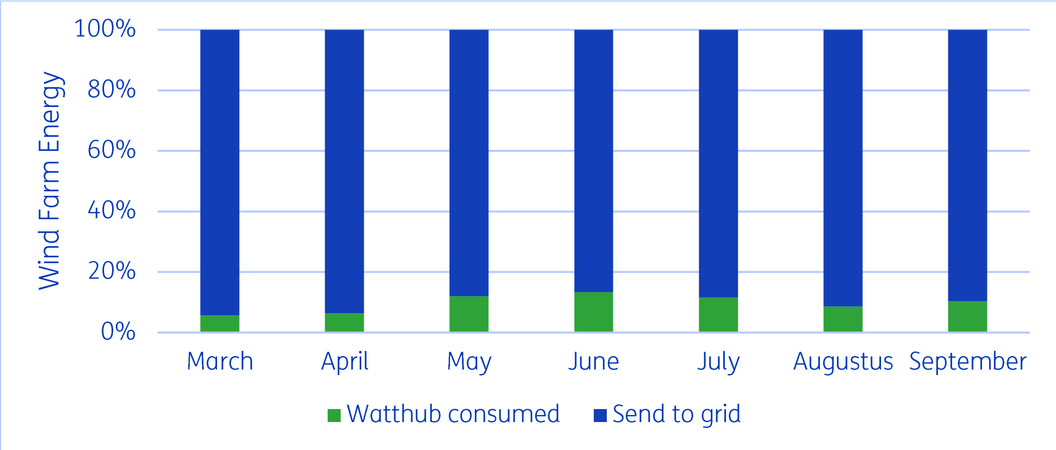


Figure 4.22: This graph shows the proportion of the wind farm's total energy production that is utilised by the WattHub.

5 Wind Park

In this chapter, the possibility of estimating wind turbine energy production is investigated. Moreover, the current performance and energy generation are investigated.

5.1 Wind farm wind turbine.

The wind park uses the Nordex N131/3600 IEC S wind turbines. The output power of the turbine is (amongst others) a function of the wind speed and air density at the turbine, see Figure 5.1.

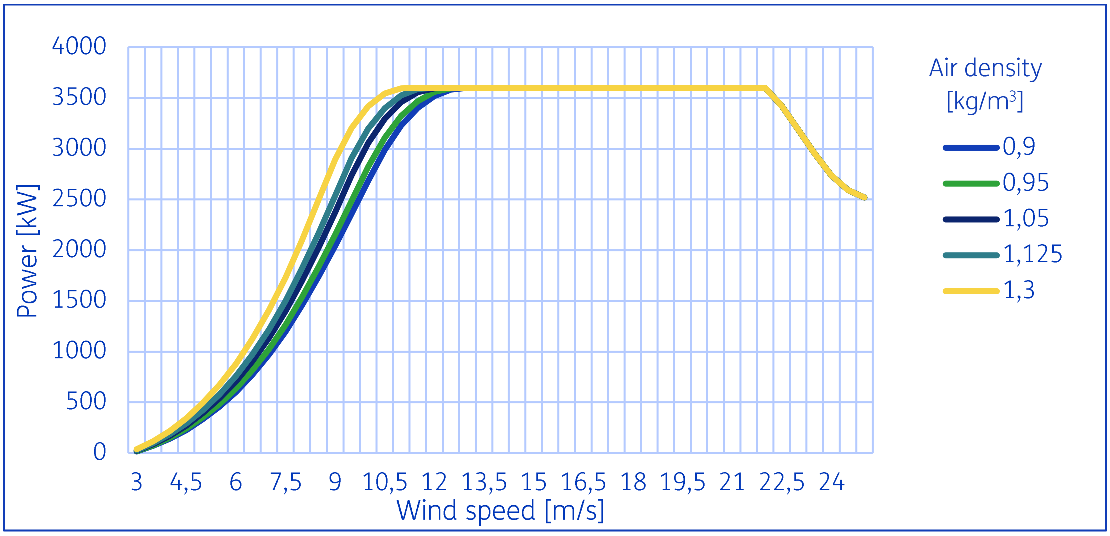


Figure 5.1: Graphs showing the Nordex N131/3600 IEC S wind power curve generation based on wind speed and air density.

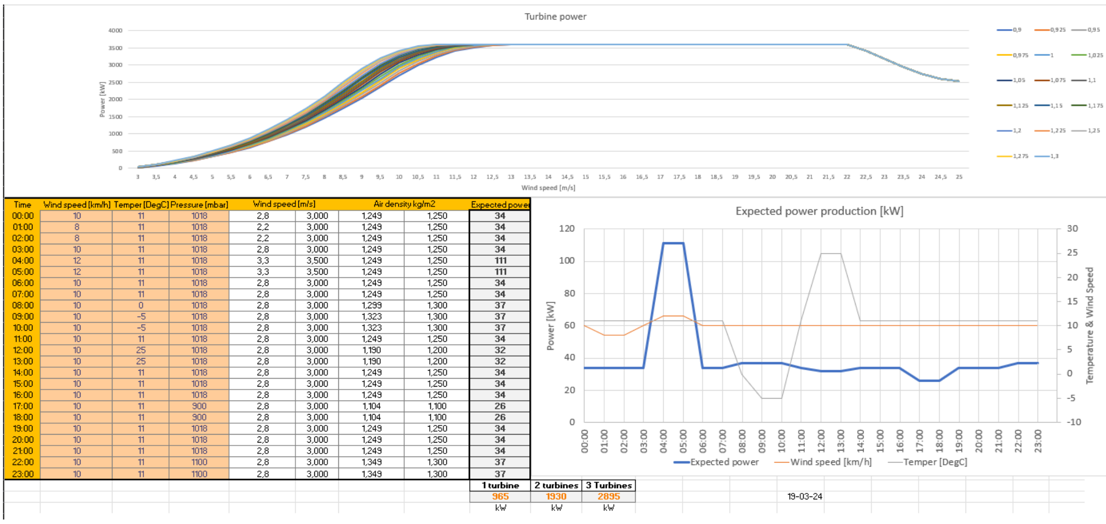
The maximum power output can be achieved with wind speeds between 10 and 21 m/s, where the power curve is flat, and air density has no significant impact. However, for wind speeds between 5 and 10 m/s, air density plays a crucial role and can influence power generation by up to 1 MW for the same wind speed.

5.2 Wind Energy Production Forecast

Given WattHub's objective of depending on renewable energy, there is a vital necessity to be able to anticipate the availability of this energy. In order to achieve this, three potential approaches to obtaining a forecast, are available.

1. **Very low accuracy** based on the turbine's wind power generation curve and free weather forecasts.
2. **Low accuracy** based on the turbine's wind power generation curve and paid weather forecasts.
3. **Moderate to high accuracy** using paid forecasting models.

The first and second approaches rely on self-calculated energy estimates based on the turbine specifications.



Time	Wind speed [km/h]	Temper [DegC]	Pressure [mbar]	Wind speed [m/s]		Air density kg/m2		Expected power
00:00	10	11	1018	2,8	3,000	1,249	1,250	34
01:00	8	11	1018	2,2	3,000	1,249	1,250	34
02:00	8	11	1018	2,2	3,000	1,249	1,250	34
03:00	10	11	1018	2,8	3,000	1,249	1,250	34
04:00	12	11	1018	3,3	3,500	1,249	1,250	111
05:00	12	11	1018	3,3	3,500	1,249	1,250	111
06:00	10	11	1018	2,8	3,000	1,249	1,250	34
07:00	10	11	1018	2,8	3,000	1,249	1,250	34
08:00	10	0	1018	2,8	3,000	1,299	1,300	37
09:00	10	-5	1018	2,8	3,000	1,323	1,300	37
10:00	10	-5	1018	2,8	3,000	1,323	1,300	37
11:00	10	11	1018	2,8	3,000	1,249	1,250	34
12:00	10	25	1018	2,8	3,000	1,190	1,200	32
13:00	10	25	1018	2,8	3,000	1,190	1,200	32
14:00	10	11	1018	2,8	3,000	1,249	1,250	34
15:00	10	11	1018	2,8	3,000	1,249	1,250	34
16:00	10	11	1018	2,8	3,000	1,249	1,250	34
17:00	10	11	900	2,8	3,000	1,104	1,100	26
18:00	10	11	900	2,8	3,000	1,104	1,100	26
19:00	10	11	1018	2,8	3,000	1,249	1,250	34
20:00	10	11	1018	2,8	3,000	1,249	1,250	34
21:00	10	11	1018	2,8	3,000	1,249	1,250	34
22:00	10	11	1100	2,8	3,000	1,349	1,300	37
23:00	10	11	1100	2,8	3,000	1,349	1,300	37

1 turbine	2 turbines	3 Turbines
965	1930	2895
kW	kW	kW

Figure 5.2 Example of Self-Calculated Forecasted Energy Production

Using this method, an hourly estimate of the wind farm's expected energy production can be established. The accuracy of this approach is currently undetermined but heavily depends on the provided wind forecast. For example, it is known that the average mean bias error (MBE) in hourly wind speed forecasts for the day ahead is approximately 1.4 m/s[3]. This error increases by about 4-6%[4] per day. For a four-day forecast, the error would increase to around 1.7 m/s (1.4 * 1.05^4 = 1.7 m/s). Air density forecasts are even harder to predict, as they depend on variables such as temperature, humidity, and pressure. With just the wind speed error alone, the worst-case strategy for a 1-day-ahead power prediction shows an error margin of 60%, rising to 85% for a 4-day-ahead prediction.

For the third option, paid models are available from several providers, such as Whiffle, Vortex, DNV GL, AWS Truepower, and Meteodyn. Comparing these services is beyond the scope of this project, so this option will not be explored further.

When analysing monthly wind energy expectations, data from the KNMI for Dutch offshore wind farms show annual wind energy production trends. From this data, it is evident that energy production decreases between April and September as seen in the Figure 5.3.

3 Weather-data-accuracy - wind-speed
4 How to get the most accurate weather forecast.

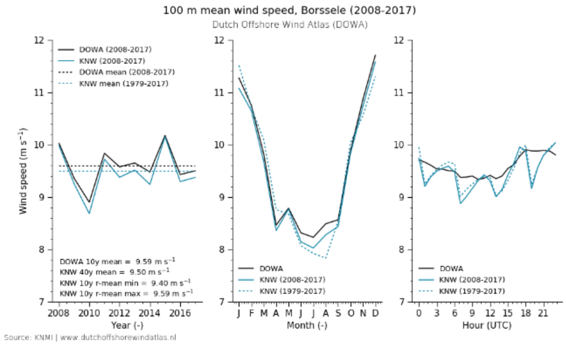


Figure 5.3: KNMI Wind data at 100 m height for yearly and long-term averages

Connecting to the solar farm is an excellent strategy to help compensate for the reduced energy production during periods of lower wind availability.

5.3 Energy Production - Data

The energy production data from the wind and solar farms, covering the period from June 1, 2022, to August 31, 2024, demonstrates the seasonal impact on energy availability from these sources. Wind and solar energy production exhibit complementary patterns, where peaks and dips in one source align with contrasting production levels in the other. This characteristic may have important implications for energy planning and management at WattHub, especially for meeting varying demand requirements throughout the year.

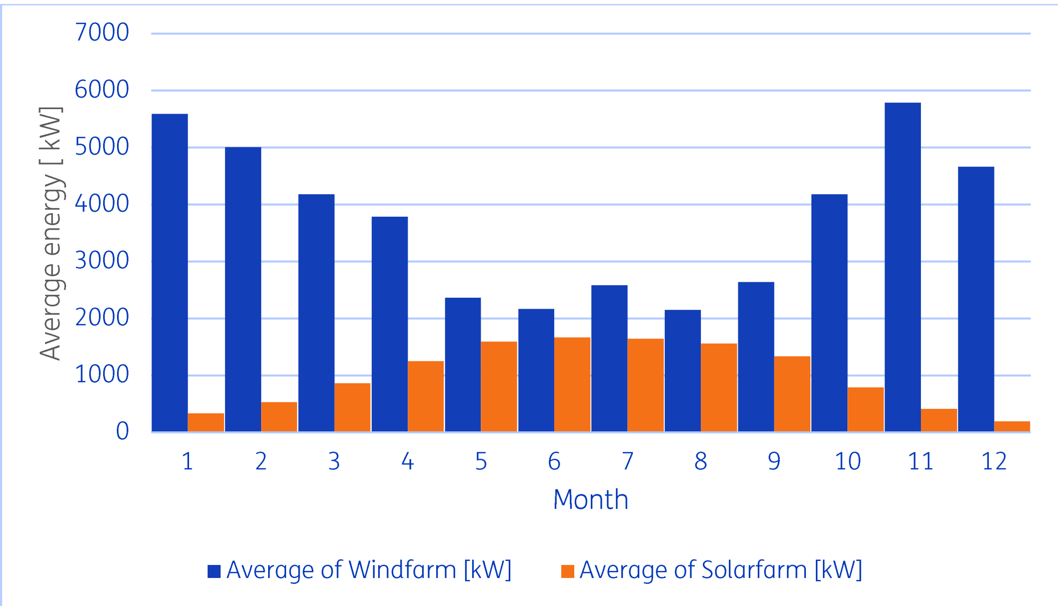


Figure 5.4: Wind and Solar production in a year

The wind farm shows peak energy production between November and February. The solar farm reaches peak production during the summer months when wind production is typically lower. This seasonal offset enhances the overall reliability of renewable energy supply by compensating for lower wind availability during warmer months.

During the summer of 2024, WattHub utilized an average of 12% of the total energy produced by the wind farm. While the presented data does not fully clarify this, it is important to note that WattHub experienced periods with no wind, during which the hub either had to rely on grid power or temporarily halt operations until wind energy became available, or the grid connection could be used.

Although the relatively low utilization of wind energy allows for the expansion of the hub, it also highlights the risk of extended periods without energy at WattHub. Therefore, connecting a solar farm would provide a reliable backup, especially during the summer months when solar energy generation is typically higher.

Examining daily production patterns further illustrates this complementary relationship. Solar energy production typically peaks during midday, when wind energy production tends to decrease. This pattern, as shown in Figure 5.5, underscores the role of solar energy in supplementing wind energy during daytime hours, especially in the summer period when wind energy is lower. The availability of solar energy during these peak demand hours reduces the strain on wind resources and ensures stable energy availability throughout the day.

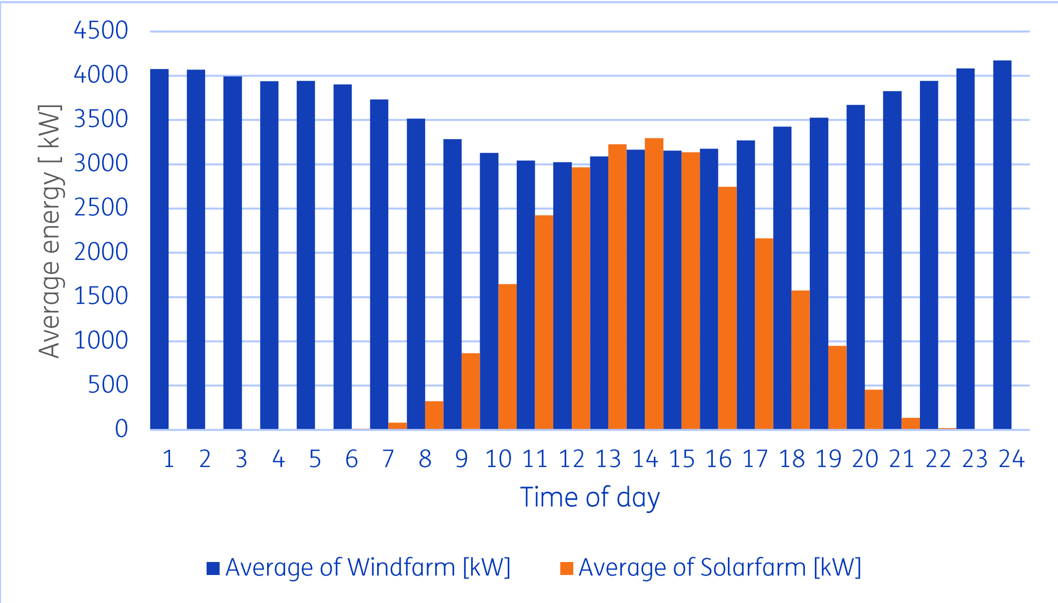


Figure 5.5: Wind and Solar production in a day (average over 2023).

The combination of wind and solar energy production provides a consistent energy supply, where seasonal and daily patterns align with the needs at the WattHub. Figures 5.4 and 5.5 illustrate the seasonal and daily production patterns of the wind and solar farms, respectively. They demonstrate that the wind farm has a significant production capacity during the winter months, while the solar farm reaches its peak production in the summer. This ensures a more constant energy delivery on a monthly scale.

6 Simulation analysis

6.1 Introduction

This analysis considers different overnight charging strategies and their impact on the energy mix (wind, solar, or grid) and peak power demand. First, measured data was processed into timeseries production and demand profiles, to represent current operations. Once established, these demand profiles were manipulated with different strategies – such as different night-time delays or limiting peak energy per charger – to see the impact.

6.2 Data

The analysis uses measured data as much as possible to represent current operations. All data use a time resolution of 15 minutes, which was the highest resolution available for the PowerLocks and renewables production.

Data Required	Timespan	Details
Production: Solar	9/2022 - 8/2024	kWh production per 15 mins
Production: Wind	9/2022 - 8/2024	kWh production per 15 mins
Demand: Power Units	6/2023 - 6/2024	Plug-In Start, Plug-In Duration, Peak kW, Total kWh
Demand: Power Locks	3/2024 - 8/2024	Total kWh - measured every 15 mins

6.2.1 Kempower Processing

The data measured from the 36 Kempower chargers provide an indication of the type of entity (vehicle or battery) charging, the time the entity plugged in, the duration of the session, and the peak power. These fields were used to group the entities into types (see Table 6.1**)**, which were then assigned charging strategies within the session window. Since the actual charging sessions (exact time and power demand during charging) were unavailable, these summary data (peak power demand, plug-in time, plug-in duration, total energy charged) were used to produce charging sessions.

Table 6.1: Types of charging entities labelled in data to distinguish charging behaviour

Type	Notes
Own Truck	Trucks identified in Mekante Diek data
Outside Truck	Other large trucks - unidentified
EV	
Powerbox	
Megabox	
Laadframe	Frame for charging multiple UMS 130 and UMS 190

Below is an example of the data transformation to build charging station profiles from summary data. The charging sessions shown meet the criteria for delayed charging (starting after 15:00, ending after 22:00, and being vehicles that can be delayed) – so the sessions are delayed until 22:00 and then charge as fast as possible.

Charging “as fast as possible” in this analysis is the total energy in 15 minutes (if not violating the peak), or peak power as long as possible until the full energy of the session is charged. This approximates the charging curves provided (visually) by Mekante Diek, as more accurate charging curves were unavailable.

Table 6.2: Example of measured data

Charging Connector:	C1	C2	C3	C4
Peak kW	147	129	130	129
Charged Energy kWh	95.686	279.555	365.765	132.458
Session Start (Local)	16:07	16:34	16:11	16:11
Duration (hh:mm:ss)	12:56:04	12:07:31	13:03:39	13:04:31

Table 6.3: Example of generated profiles

Values are in kWh	C1	C2	C3	C4
2-7-2023 21:45	0	0	0	0
2-7-2023 22:00	36.75	32.25	32.5	32.25
2-7-2023 22:15	36.75	32.25	32.5	32.25
2-7-2023 22:30	22.186	32.25	32.5	32.25
2-7-2023 22:45	0	32.25	32.5	32.25
2-7-2023 23:00	0	32.25	32.5	3.458
2-7-2023 23:15	0	32.25	32.5	0
2-7-2023 23:30	0	32.25	32.5	0
2-7-2023 23:45	0	32.25	32.5	0
3-7-2023 00:00	0	21.555	32.5	0
3-7-2023 00:15	0	0	32.5	0
3-7-2023 00:30	0	0	32.5	0
3-7-2023 00:45	0	0	8.265	0
3-7-2023 01:00	0	0	0	0

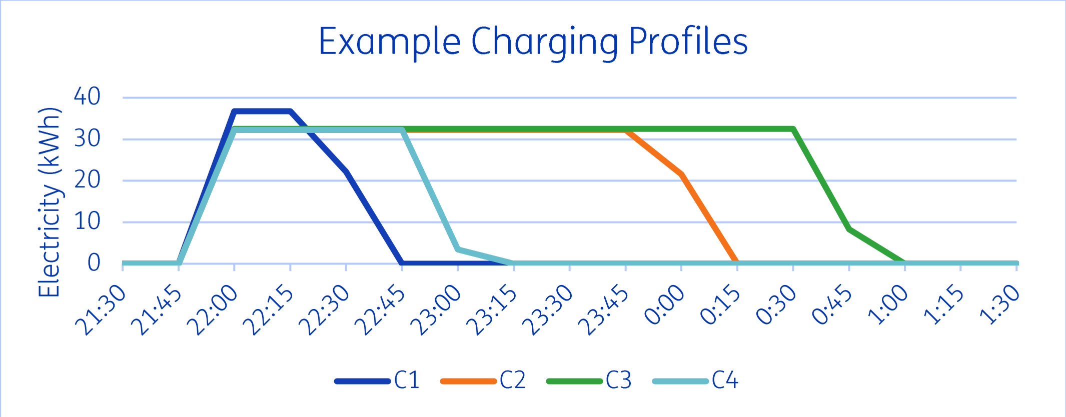


Figure 6.1: Graph of generated profile data. Vehicles charge at peak energy for as long as possible, then charge the remaining energy in the last window to reach the measured Charged Energy. The shape of the curve and the placement of the curve within the plug-in time window can be shifted to simulate strategies.

6.2.2 PowerLocks Processing

The data measured from the PowerLocks list only the change in total energy used, so this is used directly as profiles for Big-Ass Batteries. The data supplied were limited, so data from October were duplicated for November and December, and data from March were duplicated for January and February. Also, data from 2024 were reassigned to 2023 to align with the Kempower data. For all changes and reassignments, the days of the week were maintained. However, December and January will have larger demands in the analysis than in reality, due to scaled-down operations that are unmeasured.

The datetimes were also converted from UTC to EST, resulting in missing data for one hour in the spring and doubled data for one hour in the fall. We considered these faults acceptable in favour of completing the PowerLocks data for a full-year to see a more representative total demand.

6.3 Strategies

The strategy for current operations (hereafter “Current”) assumes that all vehicles charge as fast as possible during the day, but after 15:00 the following vehicles will be delayed until 22:00, if the charging session ends after 22:00[5]: Own truck, Powerbox, Megabox, and Laadframe. This is to represent current operations as closely as we can from the data.

From this Current strategy, we can create other strategies by changing the delay behaviour, or setting limitations to the peak power of each charger (see Table 6.4). Limiting peak power can be either through a kW limit (in these strategies, the same limit for all vehicles), or by a percentage of the measured peak of each session. While the measured peak is unknown before a charging session, setting a percentage peak in the simulation is a way to reduce the peaks and spread the curves of all vehicles proportionally, as opposed to the set kW peak which will impact some vehicles more than others. In strategies with multiple delay times, half of the chargers of each inverter are set to each delay time.

[5] The end of the session is generally unknown in reality, but this adjustment is made so that any “quick charges” at the end of the day are not artificially delayed, along with any subsequent session on that charger.

Table 6.4: Strategy Parameters – differences bolded

	Delay Time(s)	Peak Limit (kW)	Peak Limit %
Current	22:00	None	None
Strategy 1	**22:00, 02:00**	None	None
Strategy 2	**22:00, 02:00**	**150 kW**	None
Strategy 3	22:00	**100 kW**	None
Strategy 4	22:00	**150 kW**	None
Strategy 5	22:00	None	**75%**

All strategies only manipulated the Kempower charging profiles, because (to the best of our knowledge) Mekante Diek does not have control of the charging on the PowerLocks.

6.4 Results

Analysing the different strategies is done using calculations for demand satisfied by each type of production, then calculating other relevant results, such as the number of hours the system has to import energy from the grid.

Comparing the results from the strategies in Table 6.4, we can consider key outcomes, as covered in the following sections.

6.4.1 What is the energy mix to satisfy demand?

Figure 6.2 shows how WattHub power demand is satisfied by different energy sources for each strategy. This is a key comparison to see if strategies use more wind energy than grid imports than the Current strategy.

In all strategies, the energy supplied by wind (blue) satisfies 83.5-84.5% of total demand. Approximately 15% is supplied by import from the grid (orange + green), including the approximately 10% covered by solar production (orange). None of the strategies show a significant change in this consumption pattern.

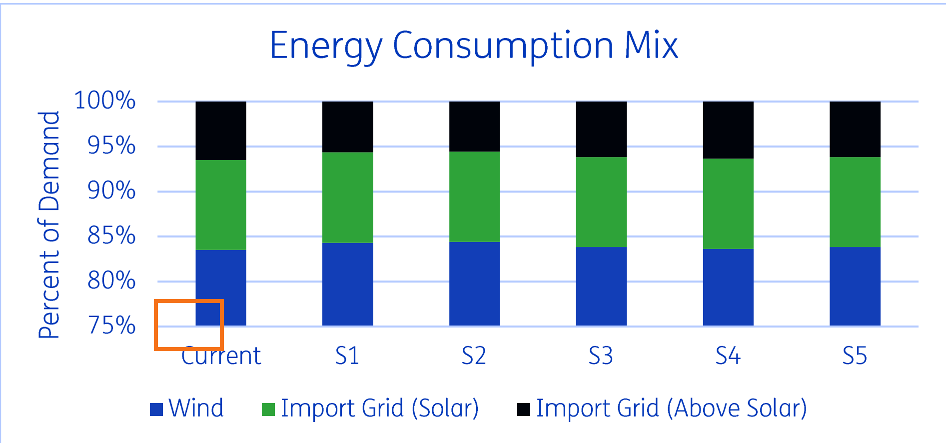


Figure 6.2: Percent of demand satisfied by different energy sources

6.4.2 How much does the system import from the grid?

The current energy contract has a limit of 600 FLH (full load hours) of import per year from the grid. Comparing the strategies in Figure 6.3, they all import from the grid a total of between 90 and 100 FLH. Grid imports beneath the simultaneous solar production are not included in the 600 FLH limit, so the total is broken into the amount within solar production (green) and the amount exceeding solar production (black) which is 30 to 40 FLH for all strategies. Strategy 2 has the lowest grid usage, but all strategies are far beneath the 600 FLH limit.

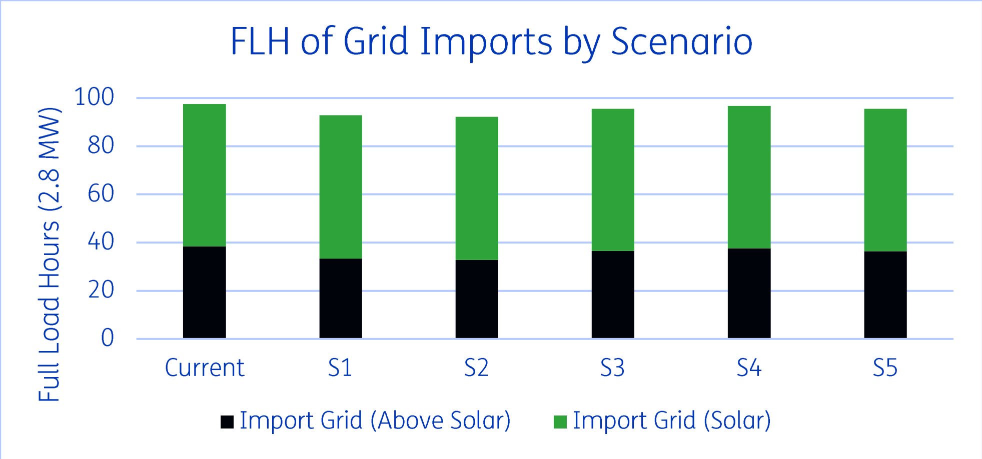


Figure 6.3: Full Load Hours that the system imports from the grid, with full load = 2.8 MW

Figure 6.4, 6.5, and 6.6 show the year maximum wind production (orange) for each timestep in a week (starting with Monday). The line shows a trend of peaks at 00:00 to 06:00 and lows at 12:00 to 18:00. The figures also show the median energy consumption by WattHub, divided into wind energy (blue), import from the grid within the solar production (green), and import from the grid that exceeds solar production (black).

Comparing the energy mix to the trends in wind production, we can see demand peaks between 07:00 and noon correspond to lower wind production and can cause importing from the grid. These peaks correlate with PowerLock demand.

In the Current strategy, there are also demand peaks at 22:00 that cause grid imports while Solar is not producing (black).

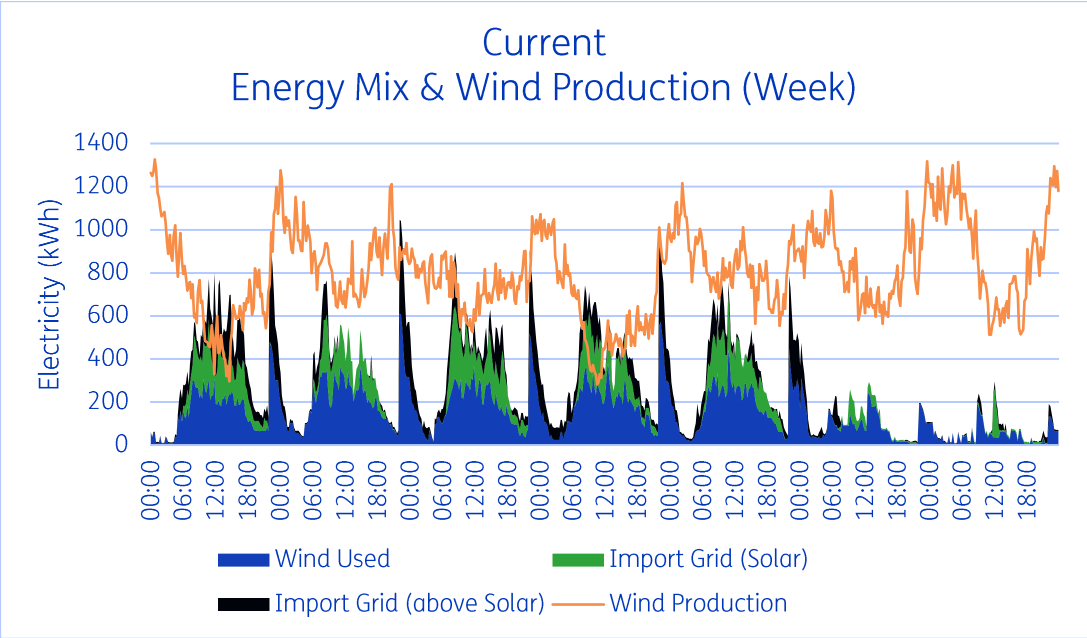


Figure 6.4: Current: Energy mix (maximum of year) compared to wind production (median of year)

Looking at the same graph for Strategy 1 (see Figure 6.5), we can see the 22:00 peak reduced, but the newly created second peak at 02:00 also causes grid imports.

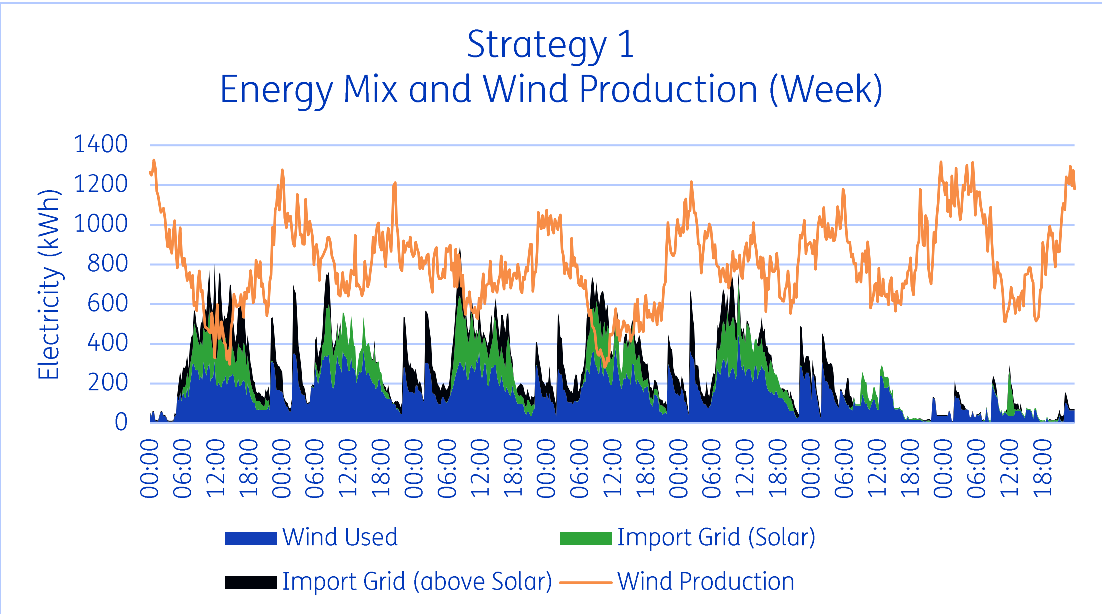


Figure 6.5: Strategy 1: Energy mix (maximum of year) compared to wind production (median of year)

Surprisingly, setting a peak limit of 100 kW per charger at night (for certain vehicles) does not have a significant effect on these peaks (see Figure 6.6) compared to the Current strategy (Figure 6.4). This implies that the extreme peaks are caused by the combination of vehicles charging simultaneously – rather than fewer vehicles with high demand – but this would require further investigation.

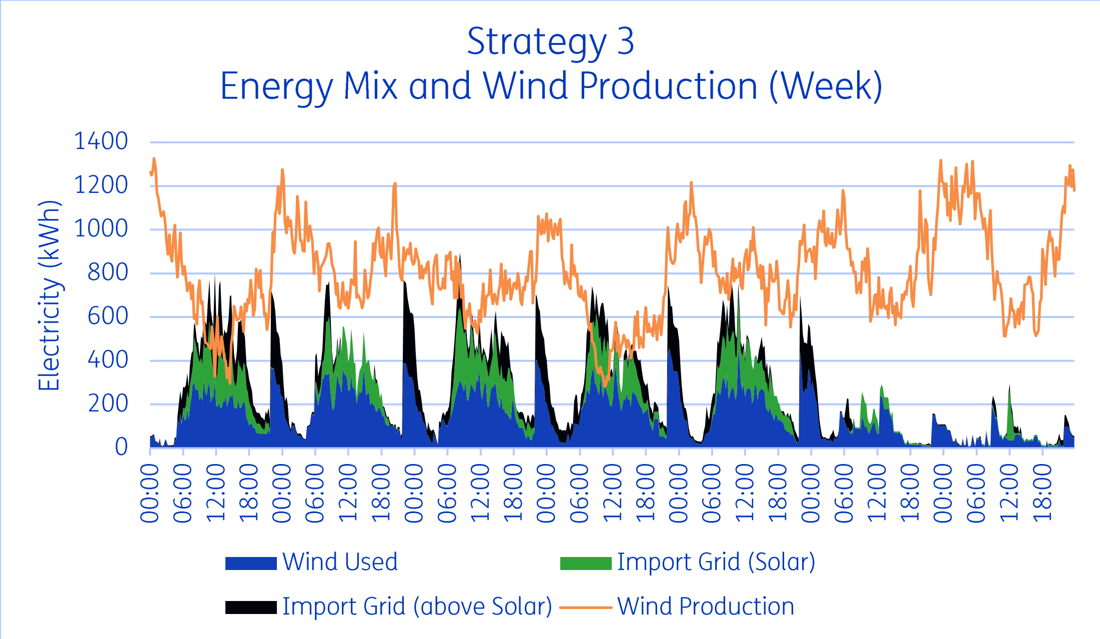


Figure 6.6: Strategy 3: Energy mix (maximum of year) compared to wind production (median of year)

6.4.3 How do the strategies impact peaks?

In Figure 6.7 we see a representative period showing the effects of the different strategies on the demand peaks and spread of charge. While the Current strategy has the highest peak, the solely capacity limiting strategies (3,4,5) succeed in reducing the major peak, with Strategy 3 (100kW limit) having the most smoothing effect.

Still, all peak-limiting strategies have higher peaks than the delay-shifting strategies (1,2). These Strategies appear quite similar, but Strategy 2 (both delay-shifting and peak limiting 150kW) has the greatest smoothing effect.

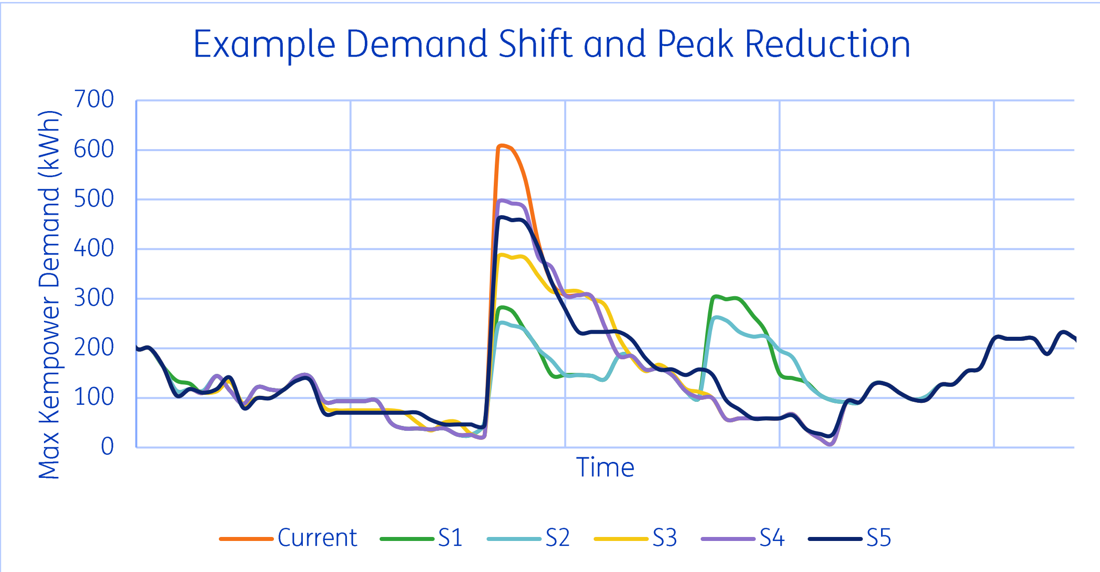


Figure 6.7: Sample of Kempower demand curves showing differences in strategies

6.5 Scenario with stationary battery storage

Initially, it was considered to determining whether there is a need for stationary battery storage at WattHub. The reasons for installing such a battery and the specific requirements would depend on the intended purpose of the installation.

Therefore, we have identified the following key reasons why a stationary battery might be considered for WattHub:

- To meet charging needs during periods of low wind energy availability;
- To take advantage of fluctuating energy prices by charging the battery during periods of low energy costs and discharging during periods of high energy prices;
- To reduce the impact of power consumption on the grid or;
- To address limitations caused by a small grid connection.

Even though WattHub focuses on maximizing the use of renewable wind energy, the primary objective is to charge all the equipment on time. The challenge of doing this is providing energy during periods of no wind. To still be able to provide renewable energy during the charging WattHub has signed an additional contract with a local Solar farm to provide energy. With this approach, WattHub mitigated the issues of not providing service during now wind.

As for reducing charging costs through battery storage, this approach currently presents significant challenges. The Mekante Diek project's power demand ranges between 2 to 8 MWh per day, excluding the demand from Power locks and other parties charging at Wathub. To meet such energy requirements, the cost of the battery storage system would be substantial (2-5 M euros), and the investment would take some time to recover. Additionally, with battery prices constantly fluctuating, investing in a stationary battery at this point does not appear to be financially viable. This conclusion aligns with the feedback received from the Mekante Diek project team.

When considering reducing impact on the grid, this has currently no application as the hub already takes most of its energy from Wind farms and not from the grid.

Lastly, currently, the available connection at WattHub is sufficient with sufficient room to grow. Even with adding megawatt chargers there currently is no incentive to consider batteries to cover the peak demand. With all of the above considerations, the conclusion was made to skip the battery consideration in the report and in the simulation.

6.6 Summary

Analysing these charge planning strategies has shown that limiting peak consumption for vehicles and more importantly shifting overnight charging sessions to multiple delay-times can impact peaks in consumption.

However, the strategies analysed failed to cause significant differences in energy consumption from wind rather than importing from the grid, compared to the current strategy. This showed in both the energy mix supplying WattHub and the full-load hours of import from the grid.

Further strategies to consider would be shifting or peak-limiting daytime demand, shifting or limiting PowerLocks demand to reduce morning peaks, shifting night-time demand to other hours (specifically to expected wind peaks), or possibly setting more specific strategies by vehicle types. All of these strategies should only be considered for analysis if operationally feasible to implement – which is likely not the case in limiting daytime demand or controlling the PowerLocks.

Overall, shifting or limiting nighttime charging should consider predicted peaks in wind production and, most importantly, spread charging throughout the night, as large peaks at 22:00 (or 02:00) cause imports from the grid. To reduce daytime grid imports above solar, there would first have to be operational methods for increasing flexibility – since current operations only allow immediate charging during the day, this analysis did not consider any shifts in behaviour that could reduce imports and/or increase wind energy consumption.

7 Impact on emissions

By utilizing zero-emission (ZE) equipment in this project, significant reductions in pollutant emissions and greenhouse gases (GHGs) are being achieved. This chapter outlines the emissions that have been avoided as a result. The avoided emissions are related to the operation of both non-road mobile machinery and road vehicles in this project. The emission reductions are calculated for nitrogen oxides (NO_x), particulate matter (PM) and carbon dioxide (CO_2). The calculations are based on the specific types of machinery and vehicles used, their operational deployment, energy consumption, and standardized emission factors. In this chapter different scenarios are considered, including; old (Stage I), medium-aged (Stage IIIA and IIIB), and modern (Stage IV and V) diesel equipment.

7.1 Input for emission calculations

Table 7.1 below outlines the estimated deployment details for the various machines and vehicles used in the project. The key parameters include engine power, operational days per year, daily operating hours, and the distances covered (where applicable) for different types of road traffic (urban, rural, and motorway). The hours per day and days per year were not monitored in detail, and are therefore estimations. This information provides an overview of the operational workload and energy consumption of the machinery and vehicles involved in the project, serving as a basis for emission calculations.

Non-road mobile machinery such as excavators, tractors, loaders, cranes, and other equipment typically operate 200 days per year, during (on average) 8 hours per day. Trucks have specified distances covered per day, divided between urban, rural, and motorway routes. It is estimated that the 8x4 trucks (active on the construction site) in this project, for example, cover a total of 100 km daily (60 km urban, 20 km rural, and 20 km motorway). Trucks used in road construction (as part of the asphalt set) and battery transport cover longer distances, up to 300 km per day.

Table 7.1: Estimated deployment details for the various machines and vehicles used in the project.

Machines & vehicles	Engine power [kW]	Deployment [days/year]	Deployment [hours/day]	Distance Urban / Rural / Motorway [km/day]
Excavator	100	200	8	-
Tractor	140	200	8	-
Loader	80	200	8	-
Wheeled excavator	75	200	8	-
Asphalt set	30-130	20	8	-
Silent Piler	150	90	4	-
Crane	50	90	4	-
Truck 8x4	-	200	-	60 / 20 / 20
Truck - battery transport	-	200	-	10 / 25 / 80
Truck - road construction	-	20	-	25 / 75 / 200

7.2 Emission calculations

For the non-road mobile machinery, reference emissions are calculated using several scenarios:

- Old diesel-powered equipment (Stage I);
- Medium-aged equipment (Stage IIIA and IIIB);
- Modern equipment (Stage IV and V).

In the case of Stage V equipment, assumptions had to be made regarding AdBlue consumption, which is required for NO_x reduction in the catalyst.

Two scenarios are considered for Stage V:
- Average AdBlue consumption of 6% from fuel consumption (representing low to medium engine load)[6];
- Optimal AdBlue consumption of 7% from fuel consumption (representing higher engine load).

It is anticipated that the higher engine load scenario is not uncommon for many of the machinery in this project , given the intensive activities associated with this type of project. These calculations provide a clear comparison of emissions avoided through the use of ZE equipment in place of various conventional machinery across different stages of emissions regulation. The emission calculations are based on the AUB-method. [6]

The table below presents the calculated avoided emissions for nitrogen oxides (NO_x), particulate matter (PM), and carbon dioxide (CO_2) across different scenarios for mobile machinery and trucks per year. The values are presented in kilograms (kg) for NO_x and PM, and in tons for CO_2.

[6] AUB (AdBlue verbruik, Uren, en Brandstofverbruik): een robuuste schatting van NO_x en NH3 uitstoot van mobiele werktuigen, TNO rapport 2021 R12305.

Old machinery (Stage I) contributes significantly to NO_x (12.017 kg) and PM (948 kg) emissions, with CO_2 emissions reaching 1163 tons. Medium-aged machinery (Stage IIIA and IIIB) shows a reduction in emissions, with NO_x dropping to 6916 kg, PM to 375 kg, and CO_2 to 1,047 tons. Modern machinery, shows a substantial reduction in NO_x (630 kg for "clean") and PM (8 kg for Stage V and 40 kg for Stage IV), while CO_2 emissions remain around 942 tons. Trucks emit 1007 kg of NO_x, 22 kg of PM, and 298 tons of CO_2. When excluding battery transport trucks, emissions drop to 868 kg of NO_x, 18 kg of PM, and 254 tons of CO_2.

The data illustrates the significant impact of modernizing equipment. The shift from older diesel-powered machinery to modern, cleaner alternatives reduces NO_x and PM emissions substantially, while CO_2 emissions show a more moderate reduction. Trucks, particularly those involved in battery transport, also contribute to the overall emissions profile, but efforts to optimize these vehicles can lead to further improvements.

Table 7.2: Calculated avoided emissions per year for nitrogen oxides (NO_x), particulate matter (PM), and carbon dioxide (CO_2) across different scenarios for mobile machinery and trucks

Total	NO_x [kg]	PM [kg]	CO_2 [ton]
Mobile machinery - old	12.017	948	1.163
Mobile machinery - medium	6.916	375	1.047
Mobile machinery - modern average	2.412	Stage V: 8 Stage IV: 40	942
Mobile machinery - modern clean	630	Stage V: 8 Stage IV: 40	942
Trucks	1.007	22	298
Trucks excluding battery transport	868	18	254

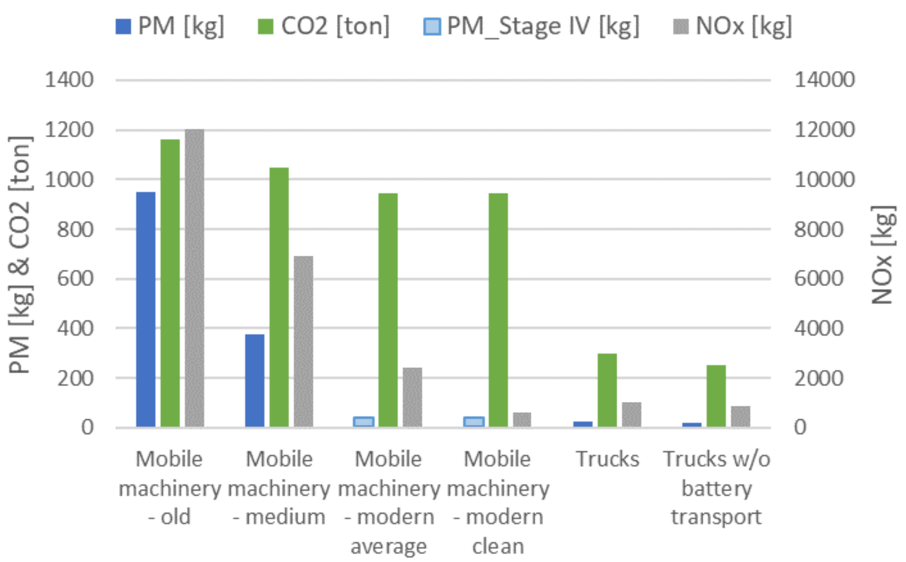


Figure 7.1: Calculated emissions per year for nitrogen oxides (NO_x), particulate matter (PM), and carbon dioxide (CO_2) across different scenarios for mobile machinery and trucks.

7.3 Emission calculations per type of machinery

In this paragraph, the avoided emissions per type of machinery and trucks are shown separately. For this purpose two scenarios are selected which are at the end of both sides of the spectrum "Mobile machinery – old" and "Mobile machinery - modern clean".

Mobile machinery – old

The graphs below provide a detailed breakdown of emissions for nitrogen oxides (NO_x), particulate matter (PM), and carbon dioxide (CO_2) for each type of **"old"** mobile machinery (Stage I). The values are given in kilograms (kg) for NO_x and PM, and in tons for CO_2.

Excavators are the largest contributor to emissions, accounting for nearly half of the total NO_x (6580 kg) and PM (521 kg) emissions, along with 640 tons of CO_2. Loaders and tractors follow, with loaders contributing 2,432 kg of NO_x and 236 tons of CO_2, and tractors emitting 1540 kg of NO_x and 147 tons of CO_2. Smaller machines like the wheeled excavator, asphalt set, silent piler, and crane contribute lower levels of emissions, with the silent piler emitting 409 kg of NO_x and 40 tons of CO_2.

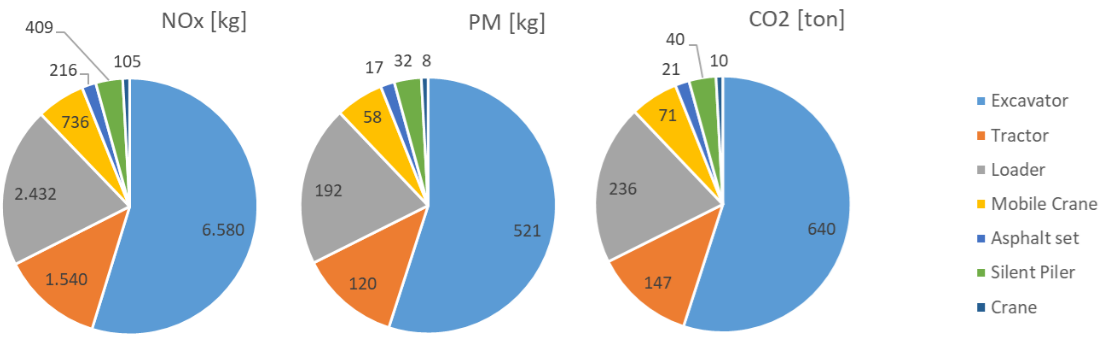


Figure 7.2: Breakdown of emissions per year for nitrogen oxides (NO_x), particulate matter (PM), and carbon dioxide (CO_2) for each type of "old" mobile machinery (Stage I).

Mobile machinery - modern clean

The graphs below outline the emissions from **"new (clean)"** mobile machinery (Stage V). Excavators remain the highest contributor to CO_2 emissions for the machinery, releasing 518 tons of CO_2, though the NO_x and PM emissions are significantly reduced to 238 kg and 4.3 kg (for Stage IV this would be 22 kg), respectively. Tractors and loaders both are the largest emission contributors after the excavators, with NO_x emissions of 80 kg and 96 kg, respectively, the same goes for PM and CO_2 emissions.

The graphs show a substantial reduction in NO_x and PM emissions compared to older machinery, demonstrating the significant environmental benefits of using modern, Stage V compliant equipment, which drastically reduces harmful emissions while maintaining relatively high CO_2 output due to energy consumption. For the transition to ZE the reductions are substantial, both for pollutant emissions and CO_2 emissions.

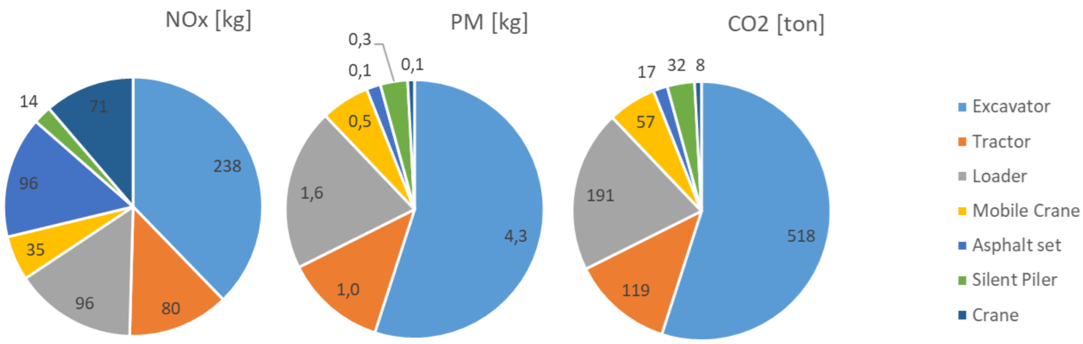


Figure 7.3: Breakdown of emissions per year for nitrogen oxides (NO_x), particulate matter (PM), and carbon dioxide (CO_2) for each type of “new” mobile machinery (Stage V).

8 Conclusions and recommendations

The main goal of this research is to analyse the operational efficiency and energy sustainability of Mekante Diek's zero-emission (ZE) equipment in combination with WattHub's charging hub. Additionally, this study explores the various factors that influence the performance of charging ZE equipment at WattHub. The findings presented in this report are primarily derived from real-world data collected throughout the project.

The study concludes that the ZE equipment used in the Mekante Diek project, charged at WattHub, offer significant energy savings and emissions reductions. With the combination of renewable energy, innovative charging infrastructure, and sustainable machinery it is shown that large-scale construction projects are possible with ZE-equipment in a sustainable way. Nevertheless, there are opportunities for improving charging efficiency. Optimizing charging schedules, expanding storage capabilities, and refining the energy reservation system may enhance the performance of the charging hub and maximize the use of renewable energy.

Key findings

Energy Consumption of ZE Equipment: Data was collected on the energy consumption of various ZE equipment used in the project, including excavators, tractors, trucks, and cranes. Data collection is an extensive process, influenced by the variety of machines and brands involved, each requiring different methods of data gathering. Not all machines provide online telemetry data, and this poses challenges in some cases. Therefore, data was not available for all machines. For the machinery and trucks with sufficient data available, the energy usage per day was determined. The data was gathered by Mekante Diek and sent to TNO. For most of the equipment, the level of detail was limited. The study found significant variability in energy usage depending on the type of equipment and its workload. For example, excavators consume between 50-85 kWh per hour, while tractors use between 12.5 and 31 kWh per hour. The study also found that the energy consumption by trucks is between 1.8 and 2.4 kWh per km, with trucks used for battery transport consuming slightly more energy. It is recommended to monitor energy consumption more extensively and link this consumption to activities. This can help to predict energy usage for the upcoming periods.

Charging Infrastructure at WattHub: WattHub has proven to be an effective charging location for trucks, construction equipment, and exchangeable batteries. It meets its design objectives by offering a seamless setup, allowing batteries to be safely placed next to chargers without requiring complex manoeuvres or additional security measures for overnight storage. The current energy contracts and infrastructure reliably supply sufficient energy for the Mekante Diek project. Notably, 90% of WattHub's power is sourced directly from the wind farm, while the remaining 10% comes from the grid. With only 15% of the available wind energy utilized so far, there is significant potential for growth and expansion.

However, some inefficiencies in the charging process have been identified. Charging sessions are often not optimally utilized, with session times accounting for up to 30% of utilization, while actual charging time is only 13%.

This highlights opportunities to improve the efficiency of the charging process. Proposed strategies include scheduled power balancing and slow charging, where the charging power is adjusted based on the expected end time of the session. This approach would take advantage of the longer connection durations

Mekante Diek charging characteristics at WattHub: WattHub serves a diverse range of clients, with the Mekante Diek consortium accounting for approximately 90% of its energy consumption (at the time of this research). The energy demand from the Mekante Diek consortium originates from three main sources for DC charging: Powerboxes (140 kWh batteries), Megaboxes (400 kWh batteries), and trucks (450–540 kWh). In June 2024, Megaboxes constituted 50% of the energy usage, trucks contributed 35%, and the remaining demand was met by Powerboxes. The median charge levels per event were 275 kWh for Megaboxes, 90 kWh for Powerboxes, and 150 kWh for trucks, with higher values typically recorded during overnight charging sessions. The AC-connection is applied for the charging of battery-containers.

Charging behaviour: Charging patterns at WattHub exhibit distinct behaviours across equipment types. Powerbox charging peaks between 11 AM and 4 PM, while Megaboxes display two peak periods in the morning and afternoon. Truck charging is more broadly distributed, with significant activity observed around 4 PM, likely in preparation for the following day's operations. These patterns reveal notable variability in energy usage, influenced by operational demands. Additionally, the general absence of a base load during nights and weekends highlights an opportunity to implement a more balanced and efficient charging schedule. For instance, advancing the charging of battery containers to earlier time slots could help alleviate morning peak demand and enhance overall energy management.

Energy forecasting: The study emphasizes the significant role of weather prediction in optimizing charging schedules at WattHub. Machines and vehicles may miss opportunities to charge during periods of higher wind energy availability. Incorporating weather forecasting into charging strategies could enhance the utilization of renewable energy, particularly wind power. Devices connected for extended periods, such as those plugged in at the end of the day around 4 PM or on Fridays, are well-suited for delayed charging during times of high wind availability. Short-term weather forecasts (up to four days) can enable more efficient scheduling, allowing these devices to maximize wind power usage and help reduce reliance on grid energy.

Optimize energy consumption at WattHub: The analysis of various charging strategies – via simulation - to optimize energy consumption at WattHub showed that shifting overnight charging sessions to different times can help manage peak loads. However, these strategies did not significantly reduce grid imports or increase wind energy consumption compared to the current approach. Further strategies, such as shifting daytime demand or focusing on night-time charging aligned with wind peaks, may help, but were not simulated. Operational feasibility may limit their implementation. In particular, spreading charging more evenly throughout the night and adjusting charging behaviour based on wind forecasts could reduce grid reliance and optimize the use of renewable energy.

Impact on (avoided) emissions
A major benefit of using ZE equipment is the reduction in emissions. The study compares ZE machinery to conventional diesel equipment across different age categories (old, medium-aged, and modern). The analysis shows that ZE equipment significantly reduces both CO_2 and pollutant emissions (NO_x and PM). For instance, old diesel equipment would emit 12000 kg NO_x and 948 kg PM per year on this construction site, modern diesel powered machinery reduces these emissions to 630 kg of NO_x and 8 to 40 kg of PM. With ZE-equipment these (tailpipe) emissions are completely avoided. Additionally, ZE equipment helps avoid substantial CO_2 emissions (around 940 tons per year).

Signature

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