Low Carbon Ukraine
Policy advice on low-carbon policies for Ukraine

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Keeping the lights on in times of grid outages

Solar PV panels, battery storage systems and diesel generators

Dinara Saparova
Rouven Stubbe
Pavel Bilek

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About Low Carbon Ukraine

Low Carbon Ukraine is a project that continuously supports the Ukrainian government with demand-driven analyses and policy proposals to promote the transition towards a low-carbon economy.

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Low Carbon Ukraine
c/o BE Berlin Economics GmbH
Schillerstr. 59
D-10627 Berlin
Tel: +49 30 / 20 61 34 64 0
Fax: +49 30 / 20 61 34 64 9
info@berlin-economics.com
www.lowcarbonukraine.com

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1 Executive summary

Russia's targeted attacks against Ukraine's civilian infrastructure have led to significant electricity outages. As the rest of the country, Ukraine's schools have been suffering from frequent blackouts, disrupting the education of millions of students. This study assesses how a cost-optimal mix of solar PV panels, battery systems and diesel generators can mitigate power outages using the example of one Ukrainian school in Kyiv. The findings show that:

- Under current conditions and a variety of tested scenarios, it is **economical** to **install solar PV panels and batteries** to mitigate outages and ensure a continuous supply of electricity.
- A **cost-optimal system** includes **solar PV, batteries** and some **diesel generation** capacity, while installing only diesel generators alone is more costly due to fuel costs.
- Total annual costs for a **cost-optimal mixed system** amount to **EUR 18 thsd.** while a **diesel only scenario** is **EUR 30 thsd**. Having a **mixed system** can therefore **save almost 40% in annual costs.**
- Diesel generators mainly act as a backup to solar PV and batteries in instances of longer durations of reduced sunshine. Compared to a scenario with diesel generators only, **less than one third of diesel fuel** is required in the cost-optimal scenario, **saving costs and reducing emissions.**
- These findings hold in today's context of low regulated residential electricity tariffs and the absence of adequately high carbon prices. Savings from installing solar PV and batteries would be significantly higher in the case of cost-covering tariffs and higher carbon prices.
- While up-front investments are higher for solar PV and battery systems, the longer lifetimes compared to diesel generators can help ensure longer sustainability and reliability.

2 Introduction

Energy security has been at the top of the political agenda in Ukraine since the Russian invasion in February 2022. The ongoing attacks on the energy infrastructure painfully underline the benefits of a gradual transition to a **more decentralised energy system to strengthen its resilience**. This transition has been highlighted by President Volodymyr Zelenskiy and Prime Minister Denys Shmygal as a key pillar both to reduce the vulnerability to attacks in the short and medium term as well as to build a modern and green energy system in the medium to long run.[1] Notably, this intention matches well with Ukraine's overall future integration path into the European Union.

At the current moment, one of the crucial needs for Ukraine's people and businesses is **reducing** the **frequent power supply disruptions by using alternative sources** in case of grid outages. Due to Russia's targeted attacks against civilian energy infrastructure, Ukraine faces **an electricity deficit of 20-30% with rolling blackouts and consumption restrictions**. To mitigate such power outages, different means of uninterruptible distributed power sources are already being used by households and businesses.

The attacks on the energy system have profound effects on virtually all parts of civilian life. Among many areas, **education**, a vital foundation of any modern society, **is impaired significantly by Russia's war of aggression** leaving more than **five million children with limited access.**[2] Even those schools that are not directly damaged by artillery, missile or drone attacks are suffering from disruptions to electricity and heat supply.

Within this context, this **study compares several alternative options for supplying uninterrupted electricity to a Ukrainian school**. While this study focusses on a school building, general conclusions remain valid for other types of similar public, commercial or residential consumers. The **distributed energy sources considered in the analysis are solar PV panels, battery storage systems and diesel generators**. These technologies are assumed to complement grid electricity which is currently provided with frequent interruptions. The **study aims to find a cost-optimal mix of these technologies to meet electricity demand of one representative school in Kyiv**. The outage schedule is also approximated to match real conditions in Kyiv.

Assuming an outage level of around 70% or about 8 hours of electricity provision per day, a mix of solar PV panels, batteries and diesel generators is found to be cost-optimal to complement unreliable grid electricity. Diesel generators, in this scenario, mainly function as a backup to solar PV and batteries in instances of longer durations of reduced solar generation. Compared to a scenario with diesel generators only, less than one third of diesel fuel is required in the cost-optimal scenario which reduces total annual costs by almost 40%.

While more expensive than the cost-optimal mix, a scenario with solar PV panels and batteries only, requiring significantly more solar panels and batteries, remains slightly below total annual costs of the diesel generators only scenario.

[1] https://www.president.gov.ua/en/news/vistup-prezidenta-zi-shorichnim-poslannyam-do-verhovnoyi-rad-80113; https://www.kmu.gov.ua/en/news/pobudova-detsentralizovanoi-enerhosystemy-zrobyt-ii-mensh-vrazlyvoiu-do-vorozhykh-atak-premier-ministr

[2] https://www.unicef.org/press-releases/11-months-war-ukraine-have-disrupted-education-more-five-million-children

Thus, **in both scenarios with solar PV and batteries**, **operational savings** (reduced diesel consumption) more than **outweighs higher upfront costs for initial investments**.This is true even in the current context of low regulated residential electricity tariffs and the absence of adequately high carbon prices. In a setting with cost-covering electricity tariffs and higher carbon prices – which could reasonably be expected in the context of Ukraine's EU accession path in the coming years – savings from installing solar PV and batteries would be even more profound than calculated here.

3 Approach, considerations and scenarios

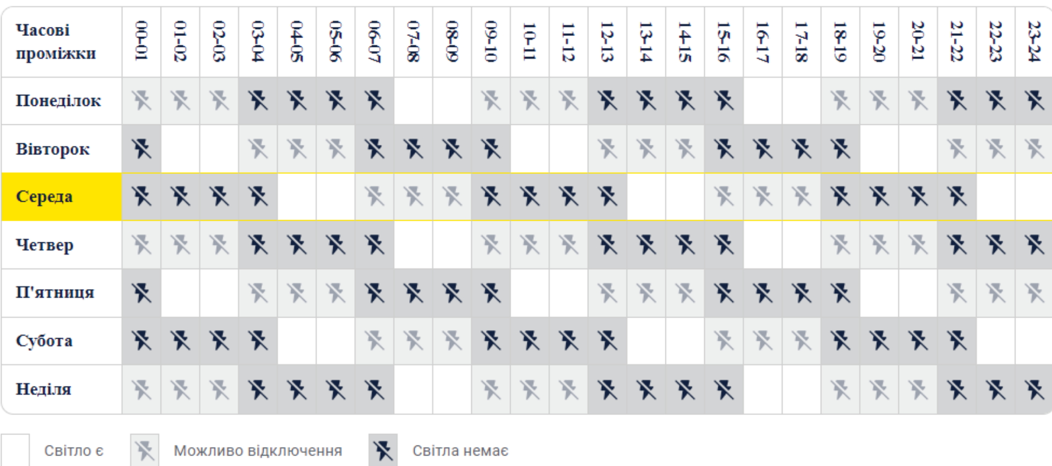
The study analyses several scenarios for supplying electricity to a representative school located in Kyiv with a maximum capacity of 600 students. The hourly standard load profile for a German school has been adapted to reflect the Ukrainian school year and holiday seasons and rescaled to match the Ukrainian school's monthly electricity demand.

3.1 Outages

Ukraine's energy system is highly centralised. Prior to the war, over 50% of electricity was supplied by four large nuclear power plants and transmitted via few ultra-high voltage lines to major consumption centres such as Kyiv. Hence, targeted attacks on power infrastructure have led to large interruptions in electricity provision. Outages can be differentiated into planned and random. Planned outages are scheduled for a predefined time period and published on the website of the distributor. These outages aim to balance system operations, for example when damaged power lines are being repaired. Random outages, however, are unpredictable emergencies in the immediate aftermath of Russian attacks.

For this analysis, outages are randomised with a typical length of four to seven hours and a frequency to match an overall outage level of 70%. This reflects current planned outage levels in Kyiv with an average availability of grid electricity of about eight hours per day (see Figure 1 below). Since additional random outages are possible due to ongoing attacks on the energy infrastructure, the randomised outage schedule approximates current realities.

Figure 1. Grid outage schedule for one exemplary week (Kyiv)

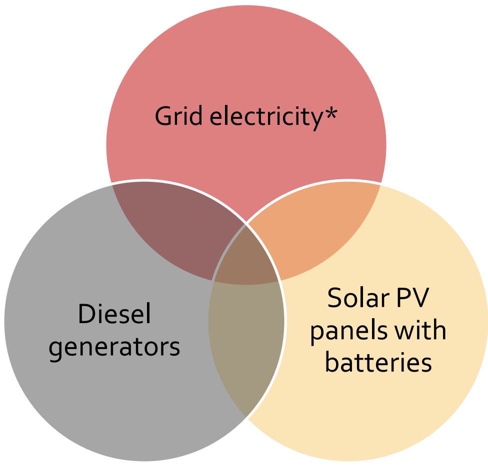


Source: DTEK Kyiv Electric Networks, 2023

3.2 Technologies

This study attempts to evaluate the economic case for using solar PV panels and battery storage systems as an alternative or complementary decentralised power source vis-à-vis traditional diesel generators. Thus, the possible technology options to complement (frequently interrupted) grid electricity are as follows:

Figure 2. Considered technologies



** with interruptions reflecting the typical length and frequency of current grid outages*
Source: own illustration

Diesel generators are a well-known and rather common solution for uninterrupted energy supply. They are characterised by their relatively low initial purchase cost. However, generators require fuel to operate, thereby introducing a constant running cost. Given recent increases and overall volatility in fuel prices, this reduces the overall attractiveness of diesel generators for relatively frequent power generation, i.e., in the context of frequent outages. On the other hand, diesel generators provide a more reliable power supply irrespective of weather conditions. This drawback can partially be resolved for solar PV panels by adding battery storage capacities.

Falling **battery and PV panel** prices have been a consistent trend throughout the last decade (with reductions of more than 80%) allowing these technologies to become cost competitive vis-à-vis traditional fossil fuel-based technologies. Overall, solar PV panels have higher capital costs than the generators, especially when combined with battery storage systems. However, running cost are very low and the expected lifetime for PV panels is quite long (20-25 years) when compared to diesel generators (typically about 8-10 years).

Detailed information on technology and fuel costs, as well as other techno-economic assumptions can be found in Annex A.

3.3 Scenarios

Based on the technologies presented above, three scenarios are designed to assess different options for decentralised electricity generation:

Table 1. Scenario overview

Scenario name	Diesel generators only	Solar PV and battery storage only	Cost-optimal mix
Grid electricity*	✓	✓	✓
Diesel generators	✓		✓
Solar PV panels		✓	✓
Battery storage		✓	✓

** with interruptions reflecting the typical length and frequency of current grid outages*
Source: own illustration

All three scenarios are analysed with a custom-built techno-economic power system model, which jointly optimises investments (in diesel generators, solar PV panels and battery storage) and hourly dispatch to meet electricity demand for a full school year from September to August.

4 Results

This section summarises the modelling results across the considered scenarios. A **mix of solar PV panels, batteries and diesel generators is found to be cost-optimal** to complement unreliable grid electricity. **Diesel generators**, in this scenario, mainly **function as a backup to solar PV and batteries** in instances of longer durations of reduced sunshine. Compared to a scenario with diesel generators only, less than one third of diesel fuel is required in the cost-optimal scenario which reduces total annual costs by almost 40%.

While more expensive than the cost-optimal mix, a scenario with solar PV panels and batteries only, requiring significantly more solar panels and batteries, is still slightly cheaper in terms of total annual costs than the diesel generators only scenario.

4.1 Installed capacities

A mix **of 26 kW solar PV panels, 25 kW diesel generators and 130 kWh of battery storage capacity** is found to be **cost-optimal for** ensuring the considered **school's electricity demand** (annual peak load of 43 kW). This capacity mix reflects the combination that fully meets demand and avoids outages at the lowest cost. When **only diesel generators** supplement grid electricity, their installed capacity reaches **42 kW**. In a scenario of **solar PV and batteries only**, the capacities are **69 kW and 814 kWh**, respectively. Higher storage capacity is required due to intermittent supply of solar power.

Table 2. Installed capacities

	Diesel generators only	Solar PV and battery storage only	Cost-optimal mix
Diesel generators (**kW**)	42	-	25
Solar PV panels (**kW**)	-	69	26
Battery storage (**kWh**)	-	814	130

Source: own modelling and calculations

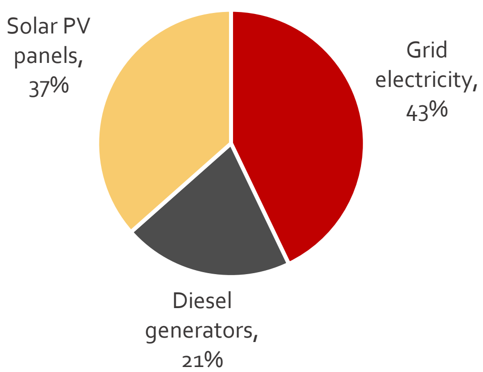
In a full off-grid scenario (please see Annex B for more details), the cost-optimal system is characterised by higher installed capacities of solar PV (53 kW) and diesel generators (33 kW) along with decreased battery storage capacity (48 kWh). Increased generation capacities reflect the lack of (even interrupted) grid electricity, as well as the need to account for the varying solar availability, especially in winter times, in the absence of long-term seasonal storage technologies.

4.2 Generation shares

Despite only being available for about 8 hours per day, **grid electricity covers over 40% of total electricity consumption** in the cost-optimal scenario (Figure 3). This is due to the fact that **grid electricity is** also **used to charge up the battery storage system** in those hours it is available (as illustrated by the spikes in Figure 6). This is consistent with real-world patterns wherein Ukrainians are already charging up their power banks during hours with grid supply**. Solar PV panels serve** the second largest share of energy consumed with **close to 40%.** Similar to grid electricity, batteries contribute to shifting solar generation to those hours where it is most needed.

Diesel generators, in the cost-optimal scenario, **cover just over 20%** of electricity needs and mainly **function as a backup to solar PV and batteries** in instances of longer durations of reduced solar generation. This is illustrated by the fact their capacity factor (utilisation rate) amounts to only 5.4%. Compared to a scenario with diesel generators only, less than one third of diesel fuel is required in the cost-optimal scenario.

Figure 3. Generation shares (cost-optimal scenario)



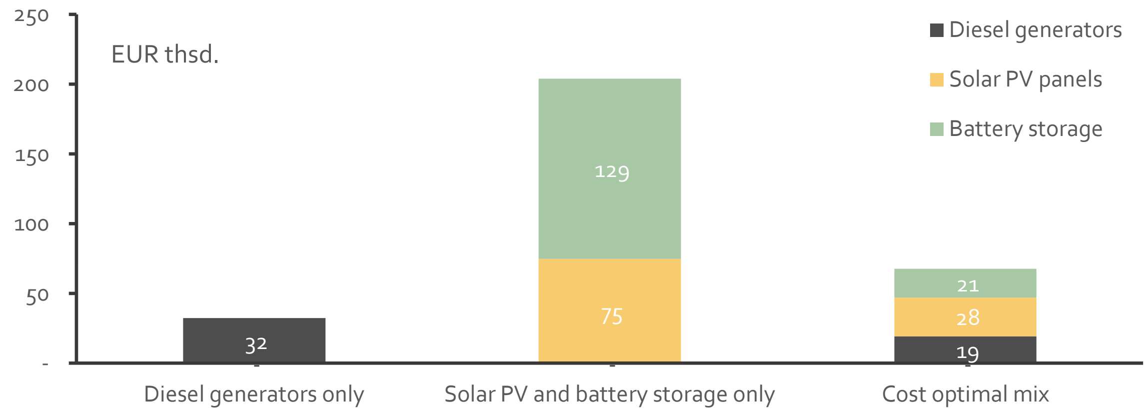
Source: own modelling and calculations

4.3 Investment and total annual cost

Aggregate investment projected for the cost-optimal system is EUR 68 thsd., more than double the up-front cost for the diesel generators only scenario (Figure 3). However, **total annual costs, which includes annualised investment costs, operation and maintenance, as well as fuel costs, amount** to almost EUR 30 thsd. for diesel generators only vs. **EUR 18 thsd. for the cost-optimal mix** (Figure 4). In the diesel generators only scenario, diesel fuel accounts for 77% of total annual costs, while fuel costs make up 40% of total annual costs in the cost-optimal scenario.

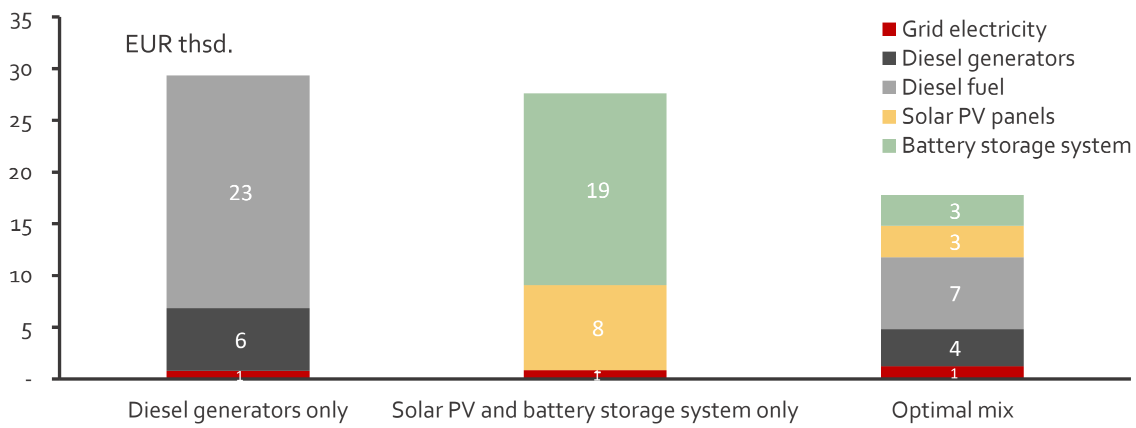
Albeit more expensive than the cost-optimal mix, a scenario with solar PV panels and batteries only, requiring significantly higher up-front investments in solar panels and batteries, remains slightly below total annual costs of the diesel generators only scenario. Thus, in **both scenarios with solar PV and batteries, operational savings (reduced diesel consumption) more than outweighs higher upfront costs for initial investments**. Additional benefits from feeding electricity back to the grid (prosumer) could further increase financial attractiveness.

Figure 4. Investment costs



Source: own modelling and calculations

Figure 5. Total annual costs

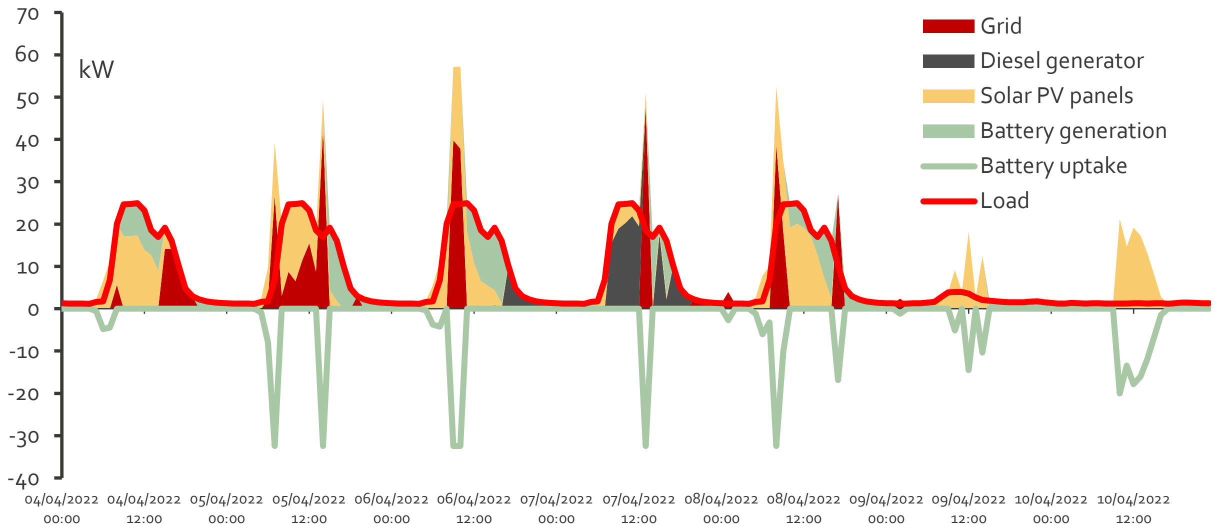


Source: own modelling and calculations

4.4 Hourly dispatch (representative week)

The representative week from 4 April to 10 April shows that the dispatch within day hours during weekdays is higher and most generation is carried out by the grid and solar PV panels. Diesel generator and battery generation are running mostly in the evening/night hours or less sunny days.

Figure 6. Dispatch in a representative week



Source: own modelling and calculations

5 Conclusion

Russia's war in Ukraine has limited educational access for more than five million children.[3] Attempts to return children into operating schools are hindered by frequent interruptions in electricity provision resulting from Russia's ongoing attacks on civilian energy infrastructure.

The analysis finds a mix of solar PV panels, batteries and diesel generators to be the most suitable option for supplying uninterrupted electricity to one representative school in Kyiv. This mix is able to reduce aggregate costs while reliably meeting the electricity demand of the school at all times. Operational savings, i.e. reduced diesel consumption, more than outweighs higher upfront costs for initial investments of solar PV panels and batteries.

This is true even in the current context of low regulated residential electricity tariffs and the absence of adequately high carbon prices. In a setting with cost-covering electricity tariffs and higher carbon prices – which could reasonably be expected in the context of Ukraine's EU accession path in the coming years – savings from installing solar PV and batteries would be even more profound than calculated here. Distributed solar generation and battery storage systems for Ukrainian schools could be the first stepping stone towards a more decentralised, resilient and future-oriented Ukrainian energy system.

[3] https://www.unicef.org/press-releases/11-months-war-ukraine-have-disrupted-education-more-five-million-children

Annex A – Modelling approach and techno-economic assumptions

The analysis has been conducted with a custom-built techno-economic power system model based on the open-source energy systems modelling framework Calliope.[4] The model jointly optimises investments in solar PV panels, battery storage and diesel generators, as well as hourly dispatch of diesel generator and solar generation, battery storage uptake and generation and grid electricity to meet electricity demand for a full school year (8760 hours) from September to August.

Hourly electricity demand for all 8760 hours is based on the quarter-hourly standard load profile for a German school from VDEW.[5] First, the standard load profile has been adjusted to a Ukrainian school year reflecting corresponding weekdays, weekends and holiday breaks for the year from 1 September 2021 to 31 August 2022. In a second step, the load profile has been rescaled to match actual monthly 2021 load of the representative school in Kyiv.

The analysis considers grid outage levels close to the status quo where the grid operates for 2721 hours per year (~30%) and the school fully relies on distributed energy resources for 6039 hours (~70%). The distribution of outages and their duration have been randomised with a typical length of four to seven hours to reflect real-world conditions (see section 3.1). The cost of grid electricity is based on the current regulated small non-household consumer tariff in Ukraine.

For the modelled generation and storage technologies, cost components can be differentiated into capital expenditures (i.e. up-front investment costs) on the one hand and operating and maintenance costs (including fuel costs) on the other hand. Cost assumptions for residential-scale equipment have been used and adjusted for Ukraine's 20% value-added tax.

- Costs for residential solar PV panels and AC-coupled lithium-ion battery storage systems are adopted from estimations by the National Renewable Energy Laboratory (NREL) for quarter 2, 2022.[6] Service cost for planning, construction and installation has been provided by the ENERGY ACT FOR UKRAINE Foundation.
- Diesel generator costs are adopted from a Rockefeller Foundation study on detailed cost models and benchmarks for electrifying communities.[7]
- The cost for diesel fuel is based on the average commercial price for diesel in Ukraine as of 26 January 2023[8].

[4] Pfenninger, S., & Pickering, B. (2018). Calliope: a multi-scale energy systems modelling framework. *Journal of Open Source Software, 3*(29), 825.
[5] Fünfgeld, C., & Tiedemann, R. (2000). *Anwendung der repräsentativen VDEW-Lastprofile: step-by-step*. VDEW.
[6] https://www.nrel.gov/docs/fy22osti/83586.pdf
[7] https://www.rockefellerfoundation.org/wp-content/uploads/2020/12/EE-Download-Opportunity-Datasheet-Detailed-Cost-Models-and-Benchmarks.pdf
[8] https://index.minfin.com.ua/ua/markets/fuel/dt/

Annex B – Off-grid scenario (cost-optimal)

Figure 7. Installed capacities

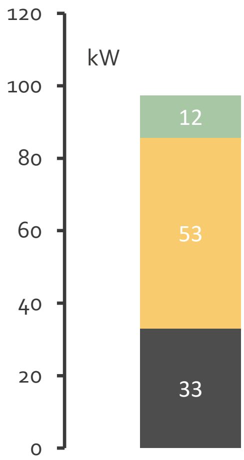


Figure 8. Investment cost

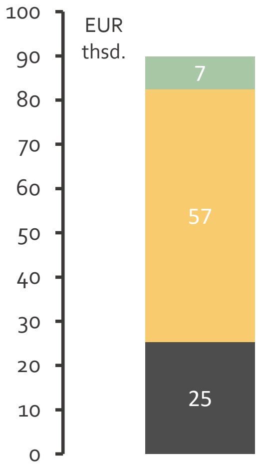
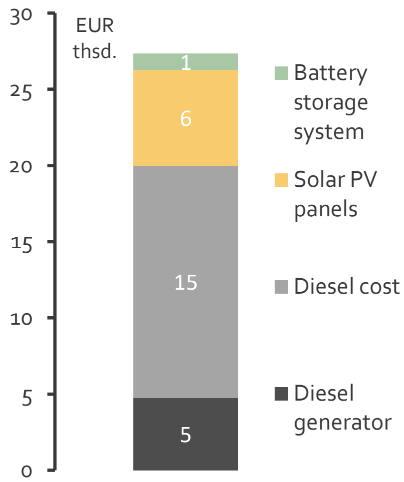
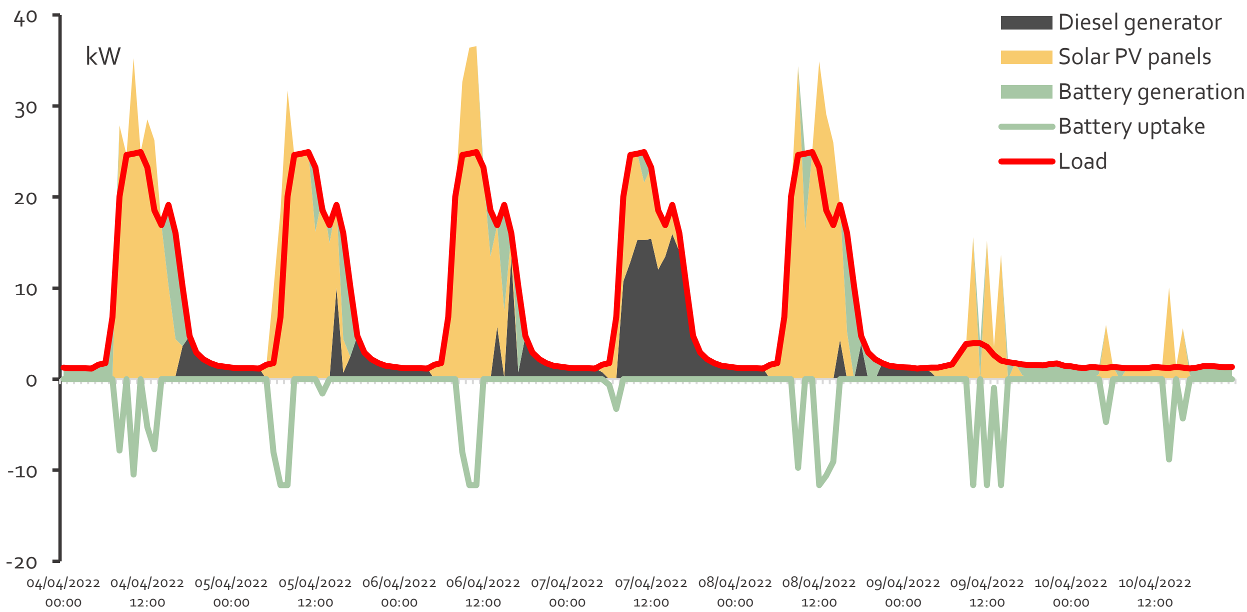


Figure 9. Total annual cost



Source (Figure 7-9): own modelling and calculations

Figure 10. Dispatch in a representative week



Source: own modelling and calculations