

Mobile Battery Energy Storage Systems for Tackling Grid Capacity Scarcity: A Cost Assessment and Market-Based Perspective

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Abstract—Limited grid capacity constrains the power available to end users. To provide additional power independently of these grid-related constraints, this paper studies the possibility to use mobile battery energy storage systems (MBESS) as an energy carrier. This concept relies on physical battery packs to deliver electricity from locations where it is abundant to locations where grid availability is insufficient. We first derive a model to determine the costs of (i) purchasing electricity to charge a battery pack with it, (ii) transporting it to a grid-constrained end-user, (iii) discharging it, and (iv) returning it back to its initial location. This full process is called the *mobile battery round-trip* (MBRT). For a 3.21 MWh mobile battery, we find a cost per unit of energy delivered using MBRT of €99/MWh (resp. €114/MWh and €144/MWh) over a round-trip distance of 50 km (resp. 100 km and 200 km). We then discuss four market structures that would enable energy exchange through mobile battery packs. Results suggest that as battery costs continue to decline, MBESS can become a viable grid-independent complement to existing infrastructure where grid reinforcement is slow or unavailable.

Keywords: Mobile battery energy storage system, Energy markets, Bilateral energy trading, Grid power access.

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I. INTRODUCTION

Since the early 2000s, the threats caused by greenhouse gas emissions have led to the electrification of various sectors. In parallel, the emergence and rapid expansion of new electricity-intensive loads, such as data centres or electric vehicles, raise electrical power demand [1–3]. This growth in power demand has increased stress on the electrical grid, including congestion issues and voltage excursions on both transmission and distribution levels [4–7]. As a result, some users are now unable to quickly obtain a new or upgraded grid connection, with waiting times taking several years [8, 9]. To reduce this delay, network operators have proposed flexible grid connections. They allow users to be connected more quickly with limited power access during grid congestion periods [10, 11]. However, this solution remains far from ideal as users may be unsatisfied with the power limit they have to comply with.

To provide additional power to restricted users, this paper studies the possibility of using mobile battery energy storage systems (MBESS) in the form of truck-mounted battery packs. In this approach, battery packs are charged at a place where

power is available and transported by trucks to be discharged in areas where local demand exceeds the local grid capacity. Battery packs could, for example, be charged at locations with sufficient grid capacity or in renewable energy farms where production would otherwise be curtailed due to grid congestion. The charged battery packs would then be transported to users limited in their grid power consumption. As battery costs are declining and are expected to fall further [12, 13], this approach may emerge as a solution to grid power access scarcity. To evaluate the potential of MBESS for supplying power-restricted end-users, i.e., grid users restricted in their power consumption, Section III models the cost of a mobile battery round-trip (MBRT). A MBRT is defined as the whole process related to purchasing electricity to charge a battery pack with it from a stationary battery at a specific location, transporting it to the end-user, discharging it into another stationary battery, and transporting it back to the initial point. The MBRT begins when electricity enters the MBESS and ends when the MBESS is back at its initial location. Stationary batteries are external assets and are excluded from the MBRT cost.

Section IV proposes four market designs to exchange battery packs. First, a regulated monopoly market, where a single battery provider operates within a specific geographic zone. Second, a monopolistic competition market, where multiple battery providers can compete in the same geographic area. Third, a two-sided platform market where battery providers and end-users would communicate buy or sell orders on a platform. The platform would serve as a link between battery providers and end-users. Fourth, a multi-sided market, in which the charging of the battery packs and their transport are decoupled, with producers, end-users and transporters interacting on a common platform. Finally, Section V concludes this paper.

II. RELATED WORKS

This section lists some related works, both regarding MBESS and general solutions to address grid capacity scarcity problems.

A. Mobile BESS

Interest in the MBESS research topic has increased in recent years, as reflected in the fast-growing body of literature on the subject.

The earliest work in the field of MBESS probably dates back to 2015 and was published by Sun et al. [14]. It proposed a concept in which MBESS are moved by trains to solve grid power congestion. They show that using MBESS could potentially reduce electrical power grid congestion and grid operation costs. Following the same idea, Liu et al. [15] propose an optimisation model to reduce the transportation costs of MBESS, reduce renewable energy curtailment and smooth the load curve. They propose two practical cases in China which illustrate that their model allows higher renewable energy penetration.

Instead of using trains, some have proposed autonomous trucks. Notably, Moghadasi et al. [16] propose an optimisation problem to minimise the operation costs, power losses, and voltage deviation in micro-grids using self-driving electric trucks for MBESS. The proposed model effectively reduces costs and power losses while improving the voltage profile. In parallel to power system operation, the concept of MBESS has also been leveraged for directly supplying an end-user electrical demand using mounted battery electric trucks, as proposed by Ernst [17].

Moving batteries charged at a given location and discharged at another location using marine transportation was also proposed. Wu et al. [18] envisage using boat-mounted MBESS to enhance cooperation between islanded microgrids, showing the viability of their model in numerical simulations. Dachet et al. [19] study the use of similar boat-mounted MBESS to transport electricity from offshore wind turbines located in the high seas to the shore. They estimate the cost per unit of electricity delivered to shore as a function of distance.

Some works focus on reducing congestion on the transmission network. This is the case of Pulazza et al. [20], which studies the potential of both MBESS and stationary batteries to reduce transmission grid congestion in high renewable energy penetration locations. They formalise an optimisation problem to minimise the annual operational cost of a transmission network. This optimisation formulation takes into account the capital and operational expenditures needed to run the system using the transmission grid, stationary BESS and MBESS.

Other works study the integration of MBESS in the distribution network. Saboori and Jadid [21] analyse the impact of MBESS in the distribution network. They propose a model to minimise the distribution network operator's daily costs. They apply this model to a case study and show reduced costs and energy losses using MBESS compared to a baseline without any MBESS. The potential of MBESS during emergencies in the distribution network was then studied [22]. They show that MBESS could significantly decrease the unmet loads while reducing curtailed renewable energy. In [23], the focus was put on balancing the use of MBESS in the distribution network to reduce renewable energy curtailment while minimising truck-mounted MBESS costs. The model shows reduced operating costs and less curtailed renewable energy on the IEEE 33-bus system [24].

Several research papers draw attention to the integration of MBESS within existing electricity markets and introduce the concept of battery-based markets. Balson et al. [25] introduce a peer-to-peer platform on which users exchange battery

packs directly with one another. In their approach, prosumers producing excess energy could order empty batteries to charge them via an app, while consumers interested in having more energy could order charged batteries. This platform concept also integrates users in charge of transporting the batteries and getting paid for this service. Qin et al. [26] develop a methodology to provide ancillary services to the grid, such as enhancing power flexibility. They propose a game-theoretic model to maximize the MBESS owners' profit. Mirzaei et al. [27] assess the impact of MBESS transported by railway in the day-ahead clearing process. They show that using MBESS could reduce total carbon emissions, daily power system operation costs and congestion. A bidding strategy for MBESS in the day-ahead electricity market, with a nodal pricing, was proposed in [28]. This work co-optimises bidding decisions with MBESS relocation, using a traffic equilibrium model to constrain feasible transfers by road-network travel time. Zhao et al. [29] compared the MBESS with their stationary alternative from a revenue perspective in a nodal pricing market. They show that MBESS could generate higher revenues in energy markets than stationary batteries.

B. Other classical solutions to tackle grid scarcity

Several solutions have been proposed to address limited grid capacity. Grid reinforcement remains the most conventional approach, as it permanently increases network transfer capability and constitutes a long-term solution. However, it requires significant investments and is often delayed by lengthy permitting procedures [30–33]. Alternative approaches seek to maximise the use of existing infrastructure. For instance, Dynamic Operating Envelopes (DOEs) trading mechanisms can reduce renewable energy curtailment and improve social welfare while respecting network constraints. Nevertheless, they require detailed knowledge of grid conditions and trading platforms, without cancelling the underlying physical limitations of the network [34].

Local electricity production can also mitigate grid access issues. Fuel-based generators are attractive because they are mature technologies, can be deployed rapidly, and operate independently from the grid. Their main drawbacks are pollutant emissions and exposure to fuel price volatility [35–38]. Similarly, solar PV systems can lower electricity purchases from the grid [39]. However, they are surface-intensive, and their output depends on weather conditions.

Energy storage solutions have also received considerable attention. Stationary batteries can support local demand. However, they still require either grid access or local generation resources for recharging [40]. MBESS propose a solution to this problem. To the best of our knowledge, none has proposed a bottom-up cost estimation for transporting MBESS from the charging point to the end-users. This paper closes that gap with a bottom-up cost model. It also discusses several market structures for exchanging MBESS.

III. MODELLING THE COSTS OF BATTERIES AS AN ENERGY CARRIER

This section proposes a bottom-up cost model for delivering electricity to end-users using MBESS transported by trucks.

It allows computing the cost of a unit of electricity delivered, given that battery packs can be charged at an electricity cost of C_{elec} . This model accounts for three categories of expenses: (i) capital expenditures (CAPEX), i.e. the investment required for each component, (ii) operational expenditures (OPEX), i.e., the costs required to operate the system, and (iii) energy expenditures, i.e., the costs of producing the electrical power to charge the batteries. Section III-A presents an overview of the MBRT for transporting battery packs between two locations. Section III-B describes each phase of the MBRT and the components required for electrical transportation using battery packs and assesses the associated expenses. Section III-C presents the proposed model for determining the MBRT cost and the related cost per unit of energy delivered using MBESS. Section III-D provides numerical results of the model. Section III-E compares this cost with that of a diesel generator, used as an alternative means of providing additional power to grid-constrained users. Finally, Section III-F discusses the results.

A. Overview of the mobile battery round-trip

We consider two locations A and B separated by a distance $d/2$, so that a complete MBRT covers a total distance d . The MBRT can be decomposed into four phases. First, the stationary battery at location A is charged with electricity withdrawn from the grid or produced locally from renewable energy sources or by conventional generators. An electric truck, powered by its own battery, then transfers an amount of electrical energy E_{char} from this stationary battery to the transported battery pack. This energy is purchased at a price per unit of electricity, C_{elec} , at a given location. Second, the truck transports its battery pack to location B . Third, the truck's battery pack discharges a quantity of electricity e into a stationary battery located near the end-user's electrical load for a cost per unit of energy delivered π_e . Fourth, the truck goes back to its initial location A with its empty battery pack. When charging the transported battery pack, a charge efficiency η_+ is considered, while when discharging it, an efficiency η_- is assumed. A schematic representation of the MBRT phases is shown in Fig. 1.

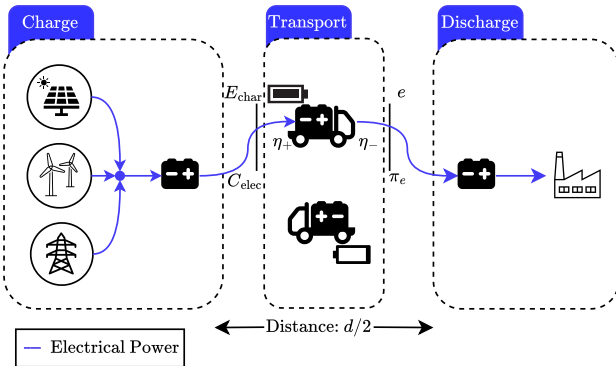


Fig. 1: Schematic representation of the MBRT, showing the four phases: charging, transportation, discharging and transporting back to the charging location.

B. Costs of components and transportation phases

We analyse the costs of each MBRT phase and the costs of the components needed to transport energy through battery packs. The components consist of the battery pack itself and the electric truck. The transportation phases are grouped into two categories: the transport itself and the battery charging/discharging.

Battery pack

The battery pack is housed in a standard 40 ft container that can be transported by truck. According to [41], the CAPEX of a new container varies between \$3500 and \$6500, which represents a cost varying between €3,097 and €5,752 according to the mean change rate for 2025 of the European Central Bank [42]. We consider the mean between these two values as the container CAPEX, $C_{\text{cont}} = €4,424.5$. According to [43], the maximal payload of a standard 40 ft container M_{cont} is 27,230 kg. The projections for batteries in 2030 give a density D_{bat} of 0.118 MWh/ton, and a cost C_{bat} of €280,000/MWh [44]. We note that these density and cost already include electronics, such as inverters, cooling systems, and cables [44]. We assume that the battery pack fully exploits the maximum payload of the container, leading to a battery pack capacity of $27.23 \cdot 0.118 = 3.21$ MWh. We assume a C-rate equal to one, a typical value for high-performance battery packs [44]. The battery pack thus has a nominal power of 3.21 MW. As highlighted by [19], the battery volume is lower than the container volume, meaning that the limiting parameter of the battery pack is its weight. It follows that the CAPEX of the 3.21 MWh battery pack composed of the battery itself and the container, denoted as C_{pack} , can be expressed as

$$\begin{aligned} C_{\text{pack}} &= 4,425 + 3.21 \cdot 280,000 \\ &= 4,425 + 898,800 = €903,225. \end{aligned}$$

Such a battery can make about $n_{\text{max}} = 6,000$ charge-discharge cycles with a lifetime of 20 years [44]. If we consider that the battery does more than one cycle per day, the battery would reach 6,000 cycles in less than $6,000/365 = 16.43$ years, which is sooner than the expected lifetime of 20 years. We therefore adopt this more restrictive cycle-based estimate as the battery's lifetime. The CAPEX per cycle of the battery pack is

$$\frac{903,225}{6,000} = €150.54/\text{cycle}.$$

We assume a fixed OPEX of €8,100/MWh/yr and zero variable OPEX [44]. To compute the OPEX per cycle, we assume one charge-discharge cycle per day. The resulting OPEX per cycle is:

$$O_{\text{bat}} = \frac{8,100 \cdot 3.21}{365} = €71.24/\text{cycle}.$$

Using the battery pack OPEX and CAPEX per cycle, we obtain a cost per charge-discharge cycle, denoted as c_{bat} , equal to

$$c_{\text{bat}} = 150.54 + 71.24 = €221.78/\text{cycle}.$$

Truck & transport

As mentioned in Section III-A, we assume that the battery packs are transported by electric trucks. According to [45], the

total cost of ownership (TCO), i.e., the total cost of owning and operating an asset over its ownership period, of a long-haul heavy-duty electric truck varies between €0.94/km and €0.91/km depending on the daily distance covered by the truck. The reported TCO values include CAPEX, OPEX, and energy expenditures, including the driver's wage. We assume a cost per kilometre for the truck, denoted as c_{truck} , equal to

$$c_{\text{truck}} = \frac{0.91 + 0.94}{2} = \text{€}0.925/\text{km}.$$

Battery charge and discharge

As assumed in Section III-A, the transported battery pack is charged from a stationary battery located at the production end. The battery is then discharged in another stationary battery located at the end-user's location. The C-rate of the considered battery pack is assumed to be equal to 1 for both charging and discharging processes [44]. This implies that the time needed for a full charge is 1 h, assuming a cable with a minimum power of $P_{\text{char}} = 3.21$ MW. A 3.75 MW cable is currently being studied and designed as part of the Megawatt Charging System (MCS) project [46, 47]. This cable could thus be used to charge and discharge the battery packs. We assume that the cable's CAPEX is already included in the battery pack electronics expenditure. Assuming the truck's driver is paid during the charge-discharge period at an hourly wage of $S_{\text{driver}} = \text{€}20/\text{h}$ based on values reported in [48, 49], the cost of the driver during charge and discharge, denoted as c_{driver} , is equal to

$$c_{\text{driver}} = 2 \cdot 1 \cdot 20 = \text{€}40/\text{cycle}.$$

We assume a charge efficiency $\eta_+ = 98\%$ [44]. To fully charge the battery pack, we must withdraw from the stationary battery

$$E_{\text{char}} = \frac{3.21}{98\%} = 3.28 \text{ MWh}.$$

If we consider this energy to be paid at a price C_{elec} , the cost of charging the battery is

$$c_{\text{char}} = E_{\text{char}} \cdot C_{\text{elec}} = 3.28 \cdot C_{\text{elec}}.$$

We assume a discharge efficiency $\eta_- = 97\%$ [44]. If we assume a fully charged battery pack at the beginning of the transportation phase and neglect the self-discharge [44], the energy delivered $E_{\text{del,max}}$ is

$$E_{\text{del,max}} = 3.21 \cdot 97\% = 3.11 \text{ MWh}.$$

C. Overall cost model

We can compute the cost of a MBRT, denoted $C_{\text{r-t}}$, of total distance d by

$$\begin{aligned} C_{\text{r-t}} &= c_{\text{bat}} + c_{\text{driver}} \\ &\quad + c_{\text{truck}} \cdot d + E_{\text{char}} \cdot C_{\text{elec}} \\ &= 261.78 + 0.925 \cdot d + 3.28 \cdot C_{\text{elec}}. \end{aligned} \quad (1)$$

If we assume the battery pack is fully charged at the beginning of the transportation, containing 3.21 MWh and the round-trip

distance d , we can compute the cost per MWh of electricity delivered per cycle, denoted $C_{\text{r-t}}^{\text{del,max}}$, as

$$C_{\text{r-t}}^{\text{del,max}} = \frac{C_{\text{r-t}}}{E_{\text{del,max}}}. \quad (2)$$

The electricity requested by the user may be lower than $E_{\text{del,max}}$. In this case, Equation (3) can be used to obtain the MBRT cost $C_{\text{r-t,e}}$, depending on the round-trip total distance d , the electricity cost C_{elec} , and the electrical energy delivered $e \in [0; E_{\text{del,max}}]$ to the user.

$$\begin{aligned} C_{\text{r-t,e}}(d, C_{\text{elec}}, e) &= c_{\text{bat}} + c_{\text{truck}} \cdot d + \frac{e}{\eta_+ \cdot \eta_-} \cdot C_{\text{elec}} \\ &\quad + 2 \cdot \frac{e}{\eta_- \cdot P_{\text{char}}} \cdot S_{\text{driver}}. \end{aligned} \quad (3)$$

The last term of Equation (3) models the driver's cost during the charging and discharging phases. We assume that the charging time is equal to the discharging time and that both are determined based on the energy stored in the MBESS of the battery-mounted truck, e/η_- . The MBRT specific cost π_e , obtained by dividing the MBRT cost $C_{\text{r-t,e}}$ by the energy delivered e , is

$$\pi_e(d, C_{\text{elec}}, e) = \frac{C_{\text{r-t,e}}(d, C_{\text{elec}}, e)}{e}. \quad (4)$$

D. Numerical results

To provide an order of magnitude on the MBRT specific cost π_e , we compute its value for three total round-trip distances $d \in \{50, 100, 200\}$ km, with the battery pack delivering $e = E_{\text{del,max}} = 3.11$ MWh and for three electricity costs $C_{\text{elec}} \in \{0, 100, 200\}$ €/MWh.¹ Results are presented in Table I. The MBRT specific cost π_e , defined by Equation (4), is plotted in Fig. 2 for four electricity costs $C_{\text{elec}} \in \{0, 100, 200, 300\}$ €/MWh, for round-trip distance $d \in [0, 200]$ km and electrical energy delivered $e \in [1, E_{\text{del,max}} = 3.11]$ MWh. We observe that the MBRT specific cost π_e increases with the round-trip distance d and decreases with the electrical energy delivered to the end-user e .

d [km]	C_{elec} [€/MWh]		
	0	100	200
50	99	204	309
100	114	219	324
200	144	249	354

TABLE I: MBRT specific cost π_e of delivered energy for different round-trip distances and electricity costs in €/MWh.

¹Setting $C_{\text{elec}} = 0$ removes the energy term $\frac{e}{\eta_+ \cdot \eta_-} \cdot C_{\text{elec}}$ from Equation (3), leaving the cost of the battery pack, the truck and the driver, i.e., the cost of the delivery service alone. It is also a plausible operating case. For example, a company operating two sites may have renewable generation at one site that can be neither consumed locally nor injected into the grid because of congestion. The opportunity cost of that energy is close to zero, and it can be transported by MBESS to the other site, where the company is short of grid capacity.

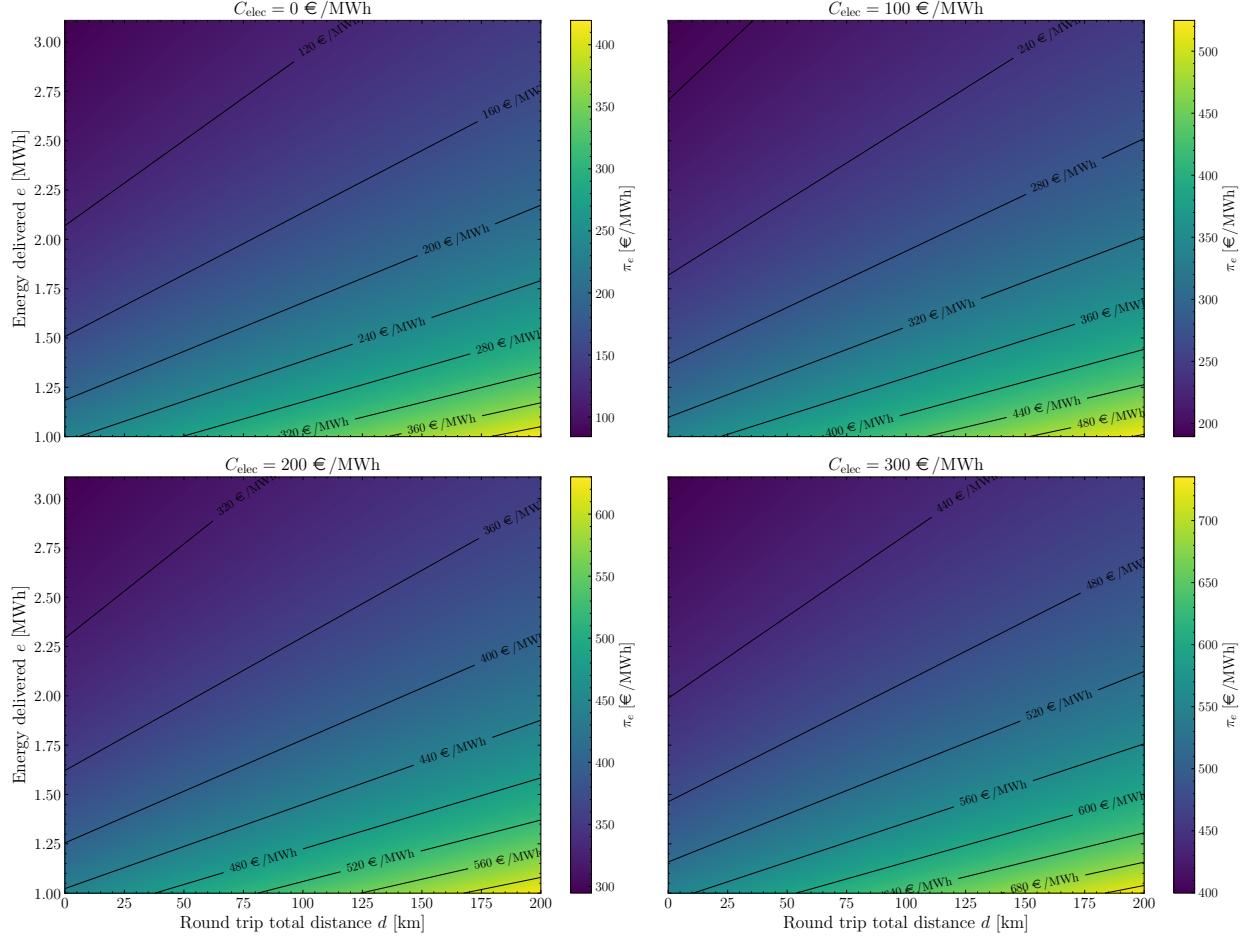


Fig. 2: MBRT specific cost $\pi_e(d, C_{\text{elec}}, e)$ of electrical energy delivered using MBESS transported by trucks.

E. Comparison with diesel generator costs

The MBRT specific cost π_e determined in Section III-C is compared in this subsection with the cost of using a diesel generator, which is one of the alternatives to the delivery of energy through MBESS. For that, we assume that the battery-truck continuously repeats the MBRT, delivering all the energy contained in its battery, $E_{\text{del,max}}$. The diesel generator is sized to deliver the same amount of electricity over the time needed to complete a MBRT. With previous assumptions, the charging and discharging phases take

$$t_{\text{char}} = t_{\text{dis}} = 1\text{h}.$$

The driving time depends on the average truck velocity, v and the round-trip total distance d . We consider $v = 45$ km/h, the average truck velocity, which is consistent with measured data [50]. The round-trip travel time, denoted as t_{travel} , is equal to

$$t_{\text{travel}} = \frac{d}{v} = \frac{d}{45}.$$

The total MBRT time, denoted as $t_{\text{r-t}}$, is the sum of the charging, discharging and travel times:

$$\begin{aligned} t_{\text{r-t}}(d) &= t_{\text{char}} + t_{\text{dis}} + t_{\text{travel}} \\ &= 2 + \frac{d}{45}. \end{aligned} \quad (5)$$

The equivalent generator has a nominal power of

$$P_{\text{gen}}(d) = \frac{E_{\text{del,max}}}{t_{\text{r-t}}} = \frac{3.11}{2 + \frac{d}{45}}.$$

Based on the Danish Energy Agency's catalogue, the CAPEX of a diesel generator is estimated at €360,000/MWe with a lifetime of 25 years [44]. Fixed OPEX of €8,983/MWe/year and variable OPEX of €6.38/MWh [44] are considered. Regarding the fuel, an average density of 10.67 kWh/l [51] and an average efficiency of 35% [44] are taken, leading to an effective energy density of 3.73 kWh/l. Assuming an average diesel cost of €0.84/l in Belgium in 2025 [52], we compute the fuel cost per MWh of electricity produced as $1000 \cdot 0.84 / 3.73 = €225/\text{MWh}$. Considering a constant electrical power demand of $P_{\text{gen}}(d)$ with d being fixed, to be furnished by the diesel generator, the annual cost of supplying this demand C_{gen} using the diesel generator solely is

$$\begin{aligned} C_{\text{gen}} &= \left(\frac{360,000}{25} + 8,983 \right) \cdot P_{\text{gen}} \\ &\quad + P_{\text{gen}} \cdot 365 \cdot 24 \cdot (6.38 + 225). \end{aligned}$$

The diesel generator specific cost, representing the cost per unit of electrical energy produced and denoted as $\pi_{\text{gen},e}$, is

equal to

$$\pi_{\text{gen},e} = \frac{C_{\text{gen}}}{365 \cdot 24 \cdot P_{\text{gen}}} = \text{€}234.05/\text{MWh}.$$

It is worth noting that this cost is constant, and so independent of distance d .

Comparing the diesel generator with MBESS requires more than the MBRT specific cost π_e alone, as the end-user must also invest in stationary battery capacity. We denote by C_{user} the cost per unit of electricity incurred by the user for both stationary battery investment and the MBRT cost. Therefore, for computing C_{user} , we add the stationary battery investment $c_{\text{bat}} = \text{€}221.78/\text{cycle}$ to the numerator of Equation (2). We assume that the stationary battery is identical to the transported one. Taking into account the stationary battery investment and the MBRT cost $C_{\text{r-t}}$:

$$C_{\text{user}} = \frac{C_{\text{r-t}} + c_{\text{bat}}}{E_{\text{del,max}}} \quad (6)$$

$$= \frac{483.56 + 0.925 \cdot d + 3.28 \cdot C_{\text{elec}}}{3.11}.$$

C_{user} increases linearly with d , whereas the diesel generator specific cost $C_{\text{gen},e}$ is constant. For a given electricity cost C_{elec} , the two curves therefore intersect at a *break-even distance*: below it, delivery by MBESS is cheaper than installing a diesel generator, and above it the generator becomes the cheaper option. Figure 3 shows these intersections for several electricity costs.

Two observations follow. First, a break-even distance exists only when the electricity is cheap enough. Solving $C_{\text{user}} = \text{€}234.05/\text{MWh}$ at $d = 0$ gives $C_{\text{elec}} \approx \text{€}74/\text{MWh}$. Above that price, MBESS delivery is more expensive than the diesel generator, whatever the distance, while below it the break-even distance grows as the electricity becomes cheaper, reaching about 264 km for $C_{\text{elec}} = 0$. Second, the competitiveness of MBESS is therefore confined to short distances and low charging costs, which is consistent with the specific costs reported in Figure 2.

F. Discussion

This subsection first considers how the MBRT cost could be reduced through the logistics of the delivery and the performance of the battery, and then examines the limitations of the result itself.

Logistics of the delivery

The driver is paid throughout the MBRT, including the two hours spent waiting for the pack to charge and discharge. Reducing this cost is therefore worth considering. Autonomous trucks could offer a solution, although their adoption faces challenges such as safety, public acceptance and liability [53]. An alternative configuration would deliver the battery pack on a trailer left at the end user's location for the duration of use, rather than transferring electrical power between battery packs. However, this approach would require rules regarding how long the end-user is allowed to keep the delivered battery-trailer. A solution could, for example, consist of dual pricing: one price based on the

energy delivered (€/MWh) and another based on the time the trailer remains at the end-user's site (€/h).

Battery performance

Alongside these practical considerations, an active field of research seeks to improve battery performance, whether through electrochemical advances [54, 55] or through improved battery management [56, 57]. The delivery cost is highly influenced by the pack characteristics, notably its charge and discharge efficiencies and maximum number of cycles supported. The maximum number of cycles supported can be increased, for example, by restricting the state of charge to a limited range and avoiding full charge and discharge. This could, however, reduce the energy delivered and, hence, increase the specific cost, as shown in Fig. 2.

Validity of the results

The results obtained must be taken as a first approximation, as the assumptions made on costs and lifetimes carry some uncertainty. To quantify the impact of parameter variations, a sensitivity analysis is provided in Appendix A.

A further limitation concerns the cost of capital, which we have set to zero. The weighted average cost of capital (WACC) is the average cost of financing a firm's assets, obtained by weighting the cost of debt and the cost of equity. It can be used within cost models through the annualised CAPEX $C_{i,\text{ann}}$ of a technology i , computed from its lifetime in years L_i as

$$C_{i,\text{ann}} = \text{CAPEX} \cdot \frac{\text{WACC}}{1 - (1 + \text{WACC})^{-L_i}}. \quad (7)$$

Lifetimes are expressed in charge-discharge cycles and in kilometres rather than in years, so L_i is not directly available, and the WACC cannot be applied as such. Assuming how intensively the technologies are used over time would supply the missing conversion. Appendix B develops this through a *utilisation rate*, from which an expected lifetime in years can be derived. This refinement matters, as the cost of capital can significantly affect the levelised cost of a technology [58].

IV. MARKET DESIGNS FOR BATTERY PACK EXCHANGE

In this section, we present four market designs for exchanging battery packs. First, Section IV-A presents a regulated monopoly market structure. Then, Section IV-B details a monopolistic competition market design, while Section IV-C introduces a two-sided platform market and the different types of platforms allowing battery pack exchange. Section IV-D then presents a multi-sided market, in which the charging and the transport of the battery packs are decoupled. Finally, Section IV-E discusses the presented markets and proposes alternative market structures.

A. Regulated monopoly market

In the proposed regulated monopoly market, a centralised provider sells electricity transported by battery-trucks to end-users. The provider is responsible for charging battery packs and transporting them within a specific geographical zone. This provider has to invest in trucks, battery packs, and

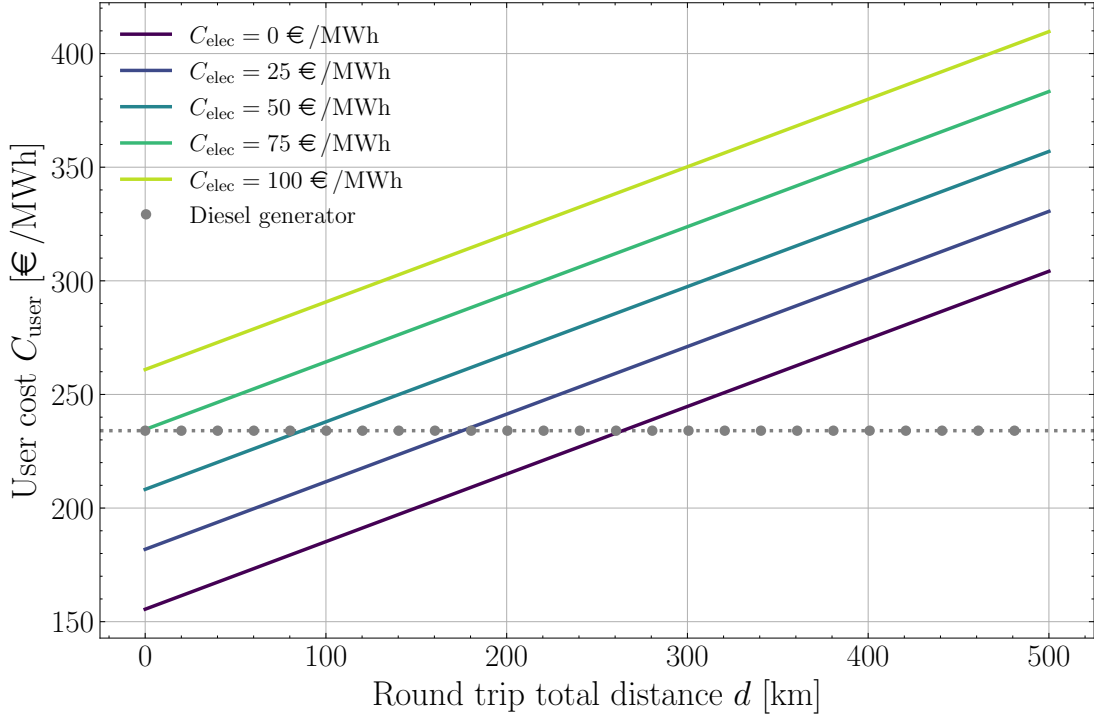


Fig. 3: Comparison of the specific cost of furnishing electricity either by using MBESS or by installing a diesel generator for different electricity costs.

charging infrastructure. The battery provider sets the price of supplying electricity, depending on the distance from the charging zone, accounting for both transportation and energy costs. To prevent abuses arising from its monopolistic position, this price is subject to a maximum set by a regulator. Users interested in receiving electricity in their stationary battery order it directly from the provider. To set its price, the provider can rely on the bottom-up cost model developed in Section III, where Equation (3) returns the cost of a delivery as a function of the round-trip distance d , the electricity cost C_{elec} , and the energy delivered e . This cost can then serve as a reference for the battery provider to propose its price, keeping in mind that the proposed price cannot exceed the one fixed by the regulator. A graphical illustration of this market is proposed in Figure 4.

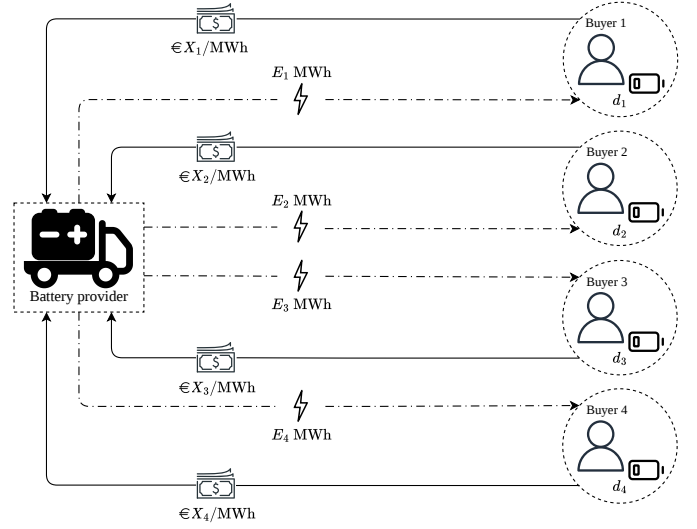


Fig. 4: Representation of four buyers $i \in \{1, \dots, 4\}$ and a battery provider interacting in the regulated monopoly market. Round-trip distances from the provider to user i , d_i and energy delivered to user i , e_i , differ among users. Consequently, the price paid by user i , X_i , also varies among users.

B. Monopolistic competition market

The monopolistic competition market was first theorised by Chamberlin [59]. The monopolistic competition states that firms and buyers operate in a certain *economic space*, defined as a multi-dimensional space, characterising how distant buyers and sellers are not only in terms of physical distance but also in other terms, such as service quality or selling prices.

Each firm holds a monopoly on buyers located in a sufficiently close economic region. However, if the firm changes its prices or service quality, it would reallocate the firm's location in this economic space and therefore the buyers over which it holds a monopoly. In this sense, there is competition between firms. In this market, more than one battery provider operates in the same geographic area. Each can set its price freely, with prices varying across providers due, for example, to differences in service quality, such as delivery speed. The buyers are then free to choose their provider based on the cost they propose and the quality of the delivery service. An illustration of this market is proposed in Figure 5.

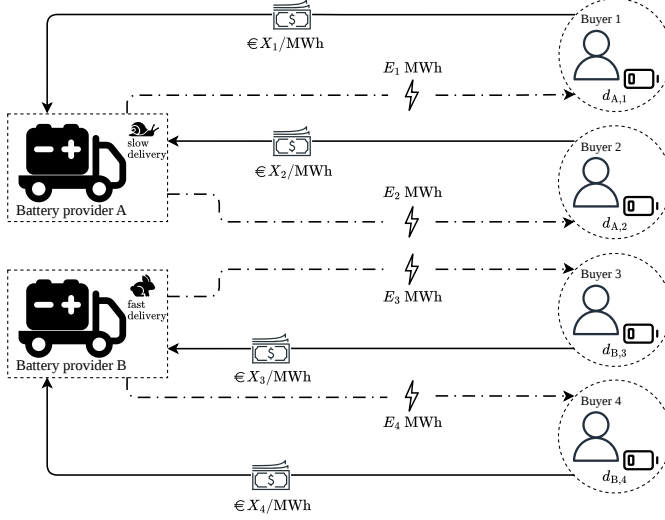


Fig. 5: Representation of four buyers $i \in \{1, \dots, 4\}$ and two battery providers $j \in \{A, B\}$ interacting in the monopolistic competition market. Round-trip distances from the provider j to user i , $d_{j,i}$, and energy delivered to user i , e_i , differ among users. Service quality, such as delivery speed, differs among battery providers. Consequently, the price paid by user i , X_i , also varies among users.

C. Two-sided platform market

In this market, the battery providers own the batteries and the trucks. They are in charge of charging and transporting the energy through their battery packs. Both battery providers and buyers communicate their orders through a platform, i.e. a digital interface that facilitates transactions between the two sides. This market can be regarded as a bilateral market. We suggest three different types of platforms to allow the exchange of energy using batteries as an energy carrier. In contrast to the monopolistic competition market presented in Section IV-B, the two-sided platform market allows both battery providers and buyers to submit *orders*. For the battery providers, the sell order minimally tells (i) the maximal amount of electricity they can offer, (ii) the maximal distance they agree to ride for the delivery, (iii) the period in which they can deliver the energy contained in the battery pack, and (iv) the price per unit of electricity they ask for the delivered energy. On the buyers' end, the buy order minimally encodes (i) the electricity they want to purchase on this market, (ii) the period they would

like to receive it, and (iii) the price per unit of electricity they agree to pay. Figure 6 proposes an illustration of this market. We discuss hereafter the three different types of platforms.

Non-contractual users' bids platform

In the non-contractual platform, users can browse the platform looking for an order corresponding to their wishes. If they are interested in an order, they are free to contact the order emitter to negotiate and, potentially, clear the deal. If they are not, they can publish their own order. The deals are contracted outside the platform. The platform thus only serves an informative purpose.

Contractual users' bids platform

This platform works similarly to the previous one, with the difference that deals can be directly contracted on it. If a user is interested in the order of another user, they can accept it on the platform. In this sense, the orders set on the platform are engaging.

Automatic matching platform

On this platform, both sellers and buyers are asked to place their orders. A match occurs when three conditions are met: (i) the delivery period coincides, (ii) the quantity of electricity proposed by the seller is higher than the one requested by the buyer, and (iii) the seller's price is lower than or equal to the buyer's price. These conditions are minimal, and additional requirements might be added for a match to occur. When a match occurs, the energy delivered corresponds to the one requested by the buyer. The transaction price, i.e., the price paid by the buyer and received by the seller, is set at the average of the seller's and buyer's price bids. This approach provides a simple and symmetric pricing mechanism, ensuring that neither party captures the entire price difference. We refer to this approach as the *average pricing strategy*. Once a match is identified, the platform automatically links the two orders, and the corresponding users only need to approve it to conclude the contract. The following example illustrates how this market platform operates.

Example on the automatic matching platform

Let us consider a buyer B and a seller S . B needs 1 MWh of additional energy in their stationary battery by noon on Friday, 14 August 2026. B decides to publish a buy order on the platform stating that they need one additional MWh of electricity in their stationary battery, for a delivery period from 13 August 12:00 PM to 14 August 12:00 PM. B agrees to pay €300/MWh. S , a battery provider, sets a sell order on the platform stating that they agree to deliver 1.5 MWh of electricity on 14 August 2026 between 10:00 AM and 11:00 AM. S requests €200/MWh and agrees to deliver within a 50 km radius of their location; B is located within that range. As the three conditions written above are met, there is a match. If B and S manually approve it and conclude the contract, one MWh of electricity will be delivered by S to B for €250/MWh, using the average pricing strategy described above.

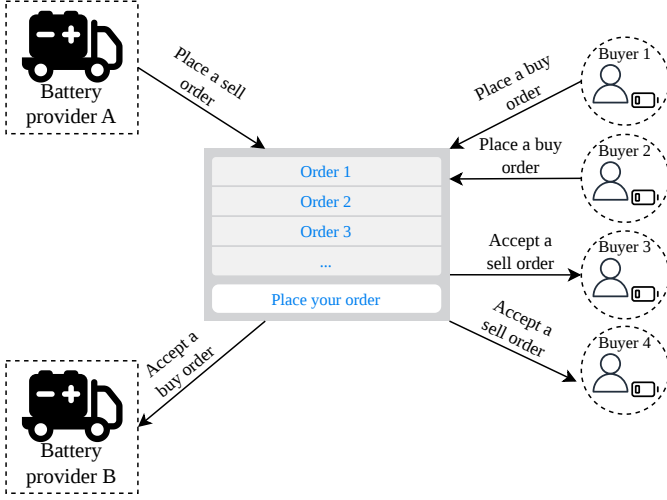


Fig. 6: Representation of the interaction with the platform in a two-sided platform market, showing the order placed and accepted by the battery providers and four buyers.

D. Multi-sided market

In the three markets presented above, the same actor charges the battery pack and transports it. The multi-sided market decouples these two activities. Three categories of users interact through a common platform: (i) electricity producers, aiming to sell the energy they store in battery packs, (ii) electricity end-users, aiming to obtain additional power, and (iii) transporters, owning the trucks and the battery packs and aiming to make a profit by providing a delivery service. The producers therefore sell energy without owning any transport asset, while the transporters sell a delivery service without ever owning the energy they carry.

This decoupling has one main consequence. It lowers the barrier to entry on both sides. A renewable energy farm can monetise electricity that would otherwise be curtailed without investing in a truck fleet, and a battery-transportation company can enter the market without investing in production assets.

As in the two-sided platform market, all three categories of users submit *orders*. The producer's sell order minimally states (i) the amount of electricity available, (ii) the period during which the battery pack can be charged at their location, and (iii) the price per unit of electricity they ask. The transporter's service order minimally states (i) the capacity of their battery pack, (ii) the maximum distance they agree to cover, (iii) the period during which they are available, and (iv) the price they ask for the delivery. The end-user's buy order minimally states (i) the electricity they want to purchase, (ii) the period during which they want to receive it, and (iii) the maximal price per unit of electricity they agree to pay, delivery included.

A match now involves three orders rather than two. It occurs when four conditions are met: (i) the charging period of the producer, the availability period of the transporter and the delivery period of the end-user are compatible, (ii) the electricity offered by the producer and the capacity of the transporter's battery pack are both higher or equal than the quantity requested by the end-user, (iii) the round-trip distance between the producer and the end-user does not exceed the

maximal distance accepted by the transporter, and (iv) the sum of the producer's price and the transporter's price is lower than or equal to the end-user's price. As in Section IV-C, these conditions are minimal and additional requirements might be added.

When these conditions are met, the surplus, i.e., the difference between the price the end-user agrees to pay and the sum of the two asks, has to be shared. We propose to split it equally between the producer and the transporter, and to set the price paid by the end-user as the average of their bid and the sum of the two asks. Other rules can be applied, as discussed in Section IV-E. An illustration of this market is proposed in Figure 7.

Example on the multi-sided market

Let us consider a producer P , a transporter T and an end-user B . P operates a solar farm whose production is curtailed on 14 August 2026 between 10:00 AM and 11:00 AM; P publishes a sell order for 3 MWh over that period at €20/MWh.² T publishes a service order stating that a 3.21 MWh battery pack is available on 14 August 2026 until 2:00 PM, for deliveries within a 50 km radius of the charging location, at €120/MWh delivered. B publishes a buy order for 3 MWh to be received on 14 August 2026 before 2:00 PM, at a maximum price of €200/MWh. B is located 50 km from P , so that the round-trip distance is $d = 100$ km.

The four conditions are met, and the sum of the two asks, €140/MWh, is lower than the price B agrees to pay. The end-user therefore pays $(200 + 140)/2 = €170/\text{MWh}$, i.e. €510 for the delivery. The €30/MWh surplus is split equally, so that P receives €35/MWh and T receives €135/MWh. Using Equation (4) with $d = 100$ km, $C_{\text{elec}} = 0$ and $e = 3$ MWh, the round-trip cost of the transporter is €117.6/MWh, leaving a margin of €17.4/MWh on this delivery.

Readers should note that matching three orders instead of two turns a bilateral matching problem into a three-sided one, for which the clearing algorithm is markedly more complex and lies beyond the scope of this paper.

²Curtailed energy is expected to be offered below the prevailing market price. Otherwise, a battery transporter would generally have no economic incentive to travel to the charging location.

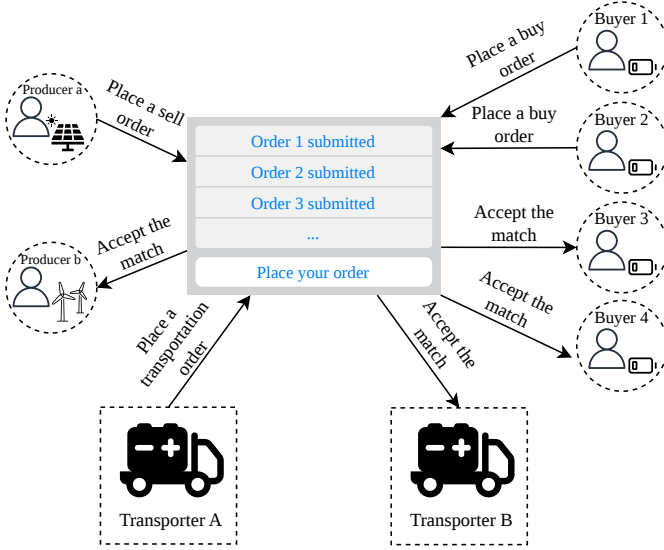


Fig. 7: Representation of the interaction with the platform in a multi-sided market, showing the orders placed by two producers, two transporters and four buyers.

E. Discussion

The markets presented here are not exhaustive. One could imagine other market structures, such as, for example, a day-ahead market with a single clearing process or an auction mechanism.

Furthermore, in the two-sided platform market and in the multi-sided market, more complex orders can be envisaged, for example, allowing recurring delivery over a defined time period, e.g. a delivery every Monday, during a year. Conditional orders could also be envisaged, where an order can only be accepted if another one is. This could be useful, for example, if two factories (A and B) are owned by the same actor, and if factory A relies on factory B for its production. If factory B cannot produce, it implies that A cannot produce either. In this case, A could place a conditional order on B, stating that their order can only be satisfied if the order of B is.

In the automatic matching platform, the paid price is set as the average of the buyer's and the seller's price. Other pricing could apply, such as a pay-as-bid strategy where the buyer pays the price they have set in their order, and the seller receives the price set in their order. The surplus could be taken by the platform owner for the service provided.

Regarding the multi-sided market, El Obadi et al. [60] propose a three-sided market-clearing problem in which a middleman does not buy the goods, but simply connects buyers and sellers and receives a payoff once the trade is done. Our multi-sided market can be interpreted as an application of this problem, with the transporters as middlemen. Its instantiation to energy trading using MBESS is left as future work.

V. CONCLUSIONS

In this paper, we propose a bottom-up model to determine the cost of transporting battery packs as a means of providing additional electrical power to users. We identify the battery characteristics, namely the charge and discharge efficiencies,

the maximum number of cycles supported by the battery, the battery energy density and the battery cost, as key factors driving the MBRT cost. We then present and describe four types of markets to allow the exchange of energy through MBESS, namely a regulated monopoly market, a monopolistic competition market, a two-sided platform market and a multi-sided market. Results suggest that transporting battery packs to provide additional power could be economically competitive, especially over short distances. Future work should (i) explore alternative market designs and further detail the proposed ones by developing market rules and pricing algorithms, (ii) establish technical standards ensuring interoperability and safety across users, and (iii) formulate co-optimisation frameworks that jointly leverage MBESS, grid access, flexibility markets, local generation, and stationary storage to maximise end-user welfare and identify cost-effective strategies for alleviating grid power scarcity.

ACKNOWLEDGMENT

The authors thank Adrien Bolland, Antoine Mouchamps, and Sammy Mokeddem for insightful discussions that helped to shape this work, and Rémi Rousset for his careful reading of an earlier version of this manuscript.

APPENDIX A

ANALYSIS OF SENSITIVITY ON THE COST MODEL

To quantify the impact of variations in the parameters used in the cost model developed in Section III, we perform a sensitivity analysis. First, let us rewrite Equation (3) that defines the cost of electricity delivered by MBESS to highlight the different parameters it depends on :

$$C_{r,t,e}(d, C_{elec}, e) = \frac{C_{cont} + M_{cont} \cdot D_{bat} \cdot C_{bat}}{n_{max}} + \frac{OPEX_{bat} \cdot M_{cont} \cdot D_{bat}}{365} + c_{truck} \cdot d + \frac{e}{\eta_+ \cdot \eta_-} \cdot C_{elec} + 2 \cdot \frac{e}{\eta_- \cdot P_{char}} \cdot S_{driver}.$$

To perform the sensitivity analysis, we fix the round-trip distance d to 100 km, the electricity cost C_{elec} to €100/MWh, and the energy delivered

$$e = E_{del,max} = D_{bat} \cdot M_{cont} \cdot \eta_-.$$

The meaning, base value, and units of the different parameters are reminded in Table II. We then perform a $\pm 10\%$ variation on the base values individually and quantify the impact on the specific MBRT cost

$$\pi_e(d = 100, C_{elec} = 100, e = E_{del,max}) = \frac{C_{r,t,e}(d = 100, C_{elec} = 100, e = E_{del,max})}{E_{del,max}}.$$

We note that the efficiencies are capped at 1, as an efficiency higher than 1 would not be physically feasible.

Parameter	Meaning	Value	Units
C_{bat}	Battery cost	280,000	€/MWh
C_{cont}	Container cost	4424.5	€
c_{truck}	Truck total cost of ownership	0.925	€/km
D_{bat}	Battery energy density	0.118	MWh/ton
η_+	Battery charge efficiency	0.98	-
η_-	Battery discharge efficiency	0.97	-
n_{max}	Battery maximal number of cycles	6000	cycles
M_{cont}	Container maximal payload	27.23	tons
$OPEX_{\text{bat}}$	Battery OPEX	8100	€/MWh/year
P_{char}	Charging cable power	3.21	MW
S_{driver}	Driver salary	20	€/h

TABLE II: Meaning, base values and units of the parameters used in the cost model.

Results are presented in Figure 8. The discharge and charge efficiencies, η_- and η_+ , have the largest impact on π_e . They are followed by the battery's maximum number of cycles n_{max} , its cost C_{bat} , its energy density D_{bat} , and the container's maximal payload M_{cont} .

APPENDIX B

FROM THE CONCEPT OF UTILISATION RATE TO THE COST OF CAPITAL

Let us define the *utilisation rate* $u \in [0, 1]$ as a measure of how much a resource, e.g. MBESS, is used compared to the maximum it could be used in a certain time period. In this section, we propose an approach to annualise the CAPEX based on an assumption on the utilisation rate. Annualising

a technology's CAPEX requires an assumption on its lifetime as indicated by Equation (7). However, the technology lifetime can be deduced from the utilisation rate.

In the case of MBESS, we can express the battery lifetime as a function of the utilisation rate. We denote by $n_{\text{max}} \in \mathbb{N}$ the maximal number of cycles a battery can support and by $n_d \in \mathbb{R}$ the average number of cycles of distance d a battery provider expects to complete daily. It follows that the expected lifetime in years, L , can be expressed as

$$L = \frac{n_{\text{max}}}{365 \cdot n_d}.$$

Using the definition of the utilisation rate and Equation (5), providing the time needed to complete a MBRT $t_{\text{r-t}}(d)$, we obtain

$$u = \frac{n_d}{24/t_{\text{r-t}}(d)}. \quad (8)$$

Based on Equation (8), we express the lifetime in years L as a function of the utilisation rate

$$L(u, d) = \frac{n_{\text{max}}}{365 \cdot n_d} = \frac{n_{\text{max}} \cdot t_{\text{r-t}}(d)}{24 \cdot 365 \cdot u}.$$

Using Equation (7) we obtain the annualised CAPEX C_{ann} as a function of the utilisation rate u and the round-trip total distance d

$$C_{\text{ann}} = CAPEX \cdot \frac{WACC}{1 - (1 + WACC)^{-\frac{n_{\text{max}} \cdot t_{\text{r-t}}(d)}{24 \cdot 365 \cdot u}}}.$$

As a reminder, the weighted average cost of capital (WACC) is defined as the average cost of financing a firm's assets, computed as a weighted combination of the cost of debt and the cost of equity, with weights corresponding to their respective shares in the capital structure.

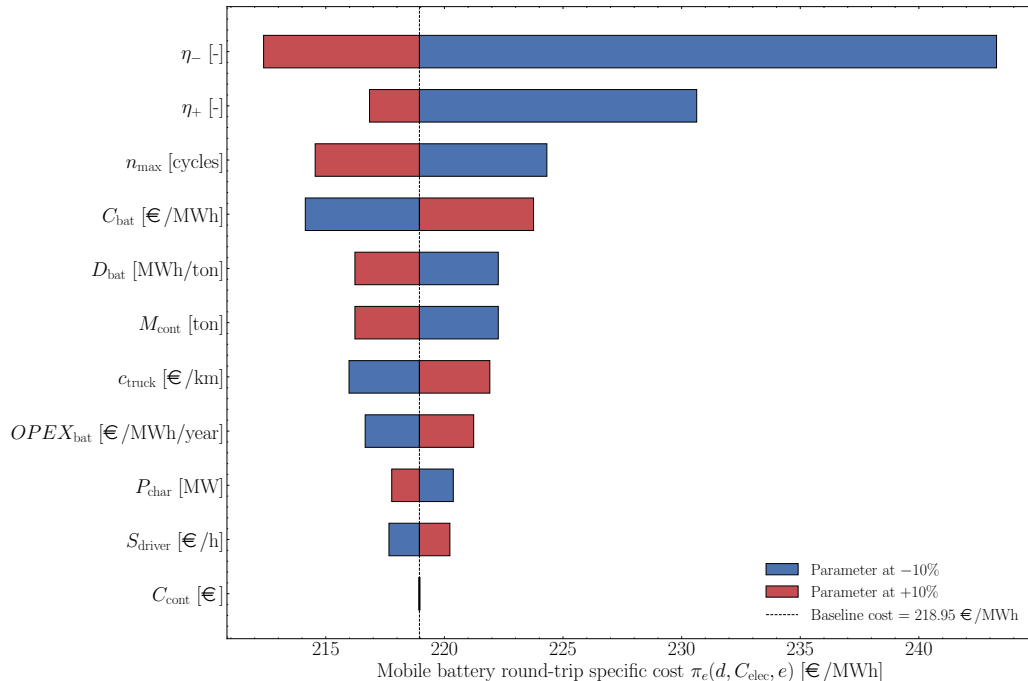


Fig. 8: Tornado diagram representing the impact of a $\pm 10\%$ variation of each cost model parameter on the MBRT specific cost.

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