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Citation for the original published paper (version of record):
Grauers, A., Gillström, H. (2026). Selecting Charging Strategy for Electric Trucks Using
Cost–Benefit Analysis—Perspective on
Operational Factors and Their Implications for Electrification. World Electric Vehicle Journal, 17(4).
http://dx.doi.org/10.3390/wevj17040189

(article starts on next page)

World Electric Vehicle Journal

Perspective

Selecting Charging Strategy for Electric Trucks Using Cost–Benefit Analysis—Perspective on Operational Factors and Their Implications for Electrification

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Abstract

Transitioning to electrified freight transport is a challenging task, and this article explores how charging strategies can be evaluated based on operational factors. The purpose is to develop a method that synthesises the core insights of the current literature and is easy to use and understand for practitioners. Therefore, it is an aim to make it as simple as possible, covering the core factors needed to find the right charging strategy, while deliberately excluding factors which only have a minor effect. The method is intended to be used to start developing an electrification strategy and can serve as a tool to decide which solutions to investigate further with more detailed methods. A cost–benefit analysis, which includes both monetary and subjective measures, is used to analyse various types of chargers and charging strategies. The novelty of the article lies in applying a systems perspective that enables a more comprehensive evaluation of charging strategies than studies that focus on specific operational factors. The results highlight five operational factors for evaluation: charging cost, productivity, flexibility, robustness, and business risk. The findings suggest that many hauliers can manage most, if not all, of their charging needs independently. Consequently, it is likely that many can begin electrifying soon, as public charging is often not critical for the electrification of their trucks. Furthermore, the article presents a decision tree to create an overview of how different driving characteristics match different charging strategies.

Keywords: electric trucks; charging strategies; cost–benefit analysis; operational factors; haulier

Academic Editor: Michael Fowler

Received: 28 January 2026
Revised: 17 March 2026
Accepted: 26 March 2026
Published: 2 April 2026

1. Introduction

1.1. Background

There is a strive to reduce global greenhouse gas emissions and national and global targets force companies to take action. The road freight transport sector is often highlighted as a large contributor to greenhouse gas emissions and according to the European Environment Agency [1], their share of CO_2 emissions is 10%. To make matters more challenging, 96% of road freight is carried using diesel trucks [2] and the sector faces an increased demand [3]. Thus, a major transition is needed. The avenue that has received much interest and has shown great potential in reducing emissions is the transition to battery electric trucks utilizing stationary charging [4,5]. This type of solution has also shown to have one of the lowest life-cycle impacts [6]. However, despite the potential to reduce emissions, the transition is moving slow due to barriers that affect the willingness of actors to pursue electrification [7,8].

The largest change in the transport system when electrifying trucks is due to the inclusion of charging and the need to plan for charging to achieve comparable service performance of the transport [9,10]. The term charging strategies is often used to describe different charging set-ups and include: the charging location, when charging takes place, and required power output [11–13]. Selecting an adequate charging strategy will be paramount for hauliers to achieve efficient transport systems with service performance comparable to diesel trucks [14].

The selection of charging strategy is, however, not straight forward and this is a gap in the current literature since many articles focus on specific aspects for assessment. There are several types of operational factors that are reoccurring in the electrification of freight transport literature that could be used to assess charging strategies. For example, Aryanpur and Rogan [4] note that charging strategies are important for achieving high productivity of electric trucks, and Zackrisson et al. [15] note that flexibility of transport operations is heavily tied to how charging is handled. Although specific operational factors can be identified in the current literature, there exist research gaps concerning which operational factors are relevant and how they can be used to evaluate charging strategies. Contributing to filling such gaps can shed light on one of the largest obstacles when it comes to electrification of road freight transport. In response, *the aim of this article is to explore how charging strategies can be evaluated based on operational factors*.

This article intends to contribute by exploring how charging strategies for electric trucks can be understood and evaluated through five key operational factors. Thus, the novelty of the article lies in its systems perspective and its ability to address a gap in the current literature, as many studies focus on specific operational factors, whereas this article provides a more comprehensive understanding of how charging strategies can be evaluated and ranked. A practical decision tree is proposed to guide hauliers in selecting suitable charging strategies based on characteristics of their transport systems. Additionally, the article outlines a simplified cost–benefit analysis to help hauliers assess the financial implications of different strategies. This empowers practitioners to integrate operational insights with their transport and business expertise.

The remaining part of this section explains the need for a systems perspective and presents the key concepts used. Section 2 outlines the method and operational factors, while Section 3 presents a cost–benefit ranking of charger types based on operational factors. The ranking is then used to compare charging strategies and create a decision tree that helps operationalize the relationship between operational factors and charging strategies. The subsequent discussion explores practical applications of the decision tree. Finally, the article concludes with a summary of key findings.

1.2. The Need for Developing a Practical Method

Being a new technology, almost all hauliers approach electrification with a lot of questions, some fear, and a need for large new investments in trucks and chargers. The problems and costs are direct and clear, while the profits are uncertain and in the future, so their decisions come with significant risk. Still, it is not possible to offer them a generic answer to how they should electrify their trucks, since they are the only ones knowing the exact conditions for their operation. Rather, this article presents a method which will help them understand the major system consequences when selecting the charging strategy for their trucks. Without the system view applied in this method, there are risks that hauliers make the wrong decisions as several system consequences are difficult to fully understand based on the traditional haulier experience. Some potential errors that can easily be made is to believe that the investments in batteries and chargers should be minimized, as they are a big and direct cost, while not understanding the many negative effects on the charging cost and operation, which comes from not owning chargers or having a small battery. Similarly, it is tempting to use public charging to reduce investment in chargers or bigger batteries, without seeing that public chargers suffer from the same issues as owned chargers, while also being a business risk.

1.3. Descriptions of Key Concepts

There are two key concepts in the article that need to be described further and positioned in the current literature: charging strategies and operational factors.

Charging strategies

The type of charging strategy used in transport flows significantly affects the effectiveness and efficiency of the transport systems [11,16]. Charging strategies can be categorized based on the power output, the location, and when the trucks are scheduled to use chargers [11,12]. Regarding power output, the two general categories are low power output and high power output [12,16].

As for location, Kin et al. [12] present three types of locations relevant for hauliers: charging at depots, charging beside the road, and charging at other premises (i.e., not own depot). As a general rule, hauliers will utilize low power charging during longer breaks (e.g., overnight at depots) since the cost for such charging is lower compared to high power output [11,13]. Charging beside the road can occur at truck stops or fuel stations, whereas charging at other premises often takes place at the destination (e.g., at the customer that receives the deliveries) [13]. These charging locations often utilize high power output to reduce the stand-still time for the trucks and avoid low productivity [9,11]. Previous research focused on the power level of the charger as a main factor for cost-effectiveness, while this article will show that charger utilization, expressed as full load hours per day, is the main factor for the cost per kWh. The power of the charger mainly has an indirect effect, since it can influence how many hours per day the charger is used.

Operational factors that determine the preferred charging strategy

As previously mentioned, several challenges hinder the adoption of electric trucks in transport systems, and selecting an adequate charging strategy becomes paramount for achieving efficient systems. Although several articles address barriers to electrification [17,18] in a general sense, no article was found that explicitly targets which factors are relevant when evaluating charging strategies. Therefore, this section describes five types of operational factors that recur in the literature and have a direct connection to the barriers mentioned in the above-cited references. The *cost of charging and infrastructure* is identified as one of the most challenging barriers by Sugihara [7]. *Productivity* and *flexibility* directly relate to some of the main barriers discussed in [17,18]. *Robustness* is vital in this context, as making changes to a well-established system increases the risk that hauliers will lose their competitiveness and market share [7]. *Business risk* is tied to the operational performance of the transport system and is linked to many of the barriers mentioned in [17,18].

The *cost of charging and charging infrastructure* is a key factor as it varies significantly, especially when comparing depot charging to public charging beside the road [11,12]. The cost for charging is mainly made up of two dominating parts: costs related to the energy that is being charged and costs related to the peak power of the charger. Since the investment cost per kW of charger power is high, the cost per kWh of charged energy will vary significantly with how chargers are used.

The *productivity* of electric trucks can, for example, be reduced if the truck carries such a heavy load that it is limited by the maximum allowed gross vehicle weight (GVW), the allowed weight per axle, or the volume [4]. In these cases, a bigger and heavier battery leads to less carrying capacity or limits the number of batteries on the truck. Productivity can also be reduced if the truck needs extra stand-still time for charging during the workday or if the truck needs to drive an extra distance to reach a charger [7].

For hauliers, *flexibility* of transport is crucial since they operate on tight schedules and need to deliver within agreed-upon time windows [15]. Including charging in the transport planning often hampers the flexibility since the location and timing become more restricted [19]. Additionally, it is more flexible if the required charging can be made at varying times and places rather than having to be done according to a strict schedule.

Robustness is a system's ability to withstand or overcome adverse conditions with no or small negative consequences, and something that hauliers must consider [20]. Applying a redundancy strategy is one way to achieve a more robust system [21]. For example, this can be achieved by having multiple chargers available to mitigate a failure of a single charger [21]. Additionally, delays of trucks should not lead to spiralling negative consequences, such as one truck being delayed at a charger, causing many other trucks to wait for their charging and subsequently also be delayed.

As the final operational factor, *business risk* is introduced, concerning the risks related to the control and availability of chargers for hauliers (inspired by [19]). The references note that control of charging availability is crucial for securing efficient systems, while the need to rely on public chargers increases business risk. Indeed, the lowest risk is often to own the chargers, but this is not always possible or suitable [19].

2. Materials and Methods

In this section, the method used to compare charging strategies is explained and the operational factors included in the comparison are explored.

2.1. Approach and Methodology

This article is classified as a perspective article since it provides a new viewpoint on an existing problem, as suggested by Editage Insights [22]. Furthermore, perspective articles should, according to Narula [23], provide novelty of a socio-economic phenomenon or innovative perspectives within a field. This description fits this article since it builds on the logic that it is not possible to find a good system design by evaluating each part of a system individually and then building the system from pieces that individually perform well (inspired by [24]). In the context of electrification, it is not possible to determine if a given charger is good or bad on its own; instead, the evaluation needs to be made for a larger system, such as a complete set of trucks and all the chargers they need, as suggested by [12,19]. Therefore, this article strives to provide a holistic evaluation that utilizes operational factors to evaluate charging strategies. By doing so, it provides a new viewpoint on how barriers associated with electrification can be managed.

Creating a comprehensive model that accounts for most factors that have some influence on how electric trucks should charge will result in a overly complex model that is impractical for practitioners. In contrast, the developed method is simple, not because many factors have been ignored while developing it, but rather since it has found a way of simplifying the problem by first showing a clear ranking between the different types of chargers. Based on the ranking, it is possible to analyse charging strategies from only a few factors, such that a less complex model can be used.

This article is based on insights gained from two research projects (REEL 2 and E-charge). Both projects began in 2021 and aim to support the transition to electrified freight transport. They incorporate perspectives from transport systems, energy systems, and charging infrastructure to provide a comprehensive understanding of the electrification landscape. Both projects engage key stakeholders such as hauliers, transport buyers, and charge point operators. As a result, the projects offer a unique opportunity to generate rare and valuable insights for actors actively involved in electrification—insights that can be likened to high-impact research [25]. The researchers have participated in seminars, presentations, and project meetings with the involved stakeholders throughout both projects. During these activities, stakeholders shared how they are working with electrification, the challenges they have encountered, and the strategies they have used to address them. These exchanges form the foundation of the insights upon which this article is built. Given the varied nature of the activities, there is no uniform way to describe each one since it was often adjusted to fit specific situations and stakeholders. It is worth noting that the number of activities exceeds ten annually. The insights have been documented through researcher notes and distributed presentations from stakeholders. Hence, the insights from the projects provide a good base for making system analyses.

The analysis method used for this article (cost–benefit analysis) has been developed based on knowledge about the technical possibilities, the economics of electric vehicle systems, and information about the operations of different hauliers. The method is developed and explained in the following steps:

- Determine which operational factors to use when evaluating charging strategies (addressed in Sections 2.2–2.6).
- Analyse individual chargers regarding these factors as an intermediate step in finding suitable charging strategies (addressed in Section 3.1).
- Define charging strategies and rank them using the operational factors (addressed in Section 3.2).
- Determine which factors related to the transport tasks and the use of the trucks that determine which charging strategy to use, and define a decision tree for selecting the charging strategy (addressed in Section 3.3).

2.2. Costs for Charging and Chargers

As previously mentioned, charger costs are mainly made up of one part, which depends on how much energy is charged, and another part depending on the peak power of the charger. Energy costs will be the same per kWh irrespective of charger size. The peak power-related cost scales almost linearly with the charger power and since the energy a charger is capable of delivering also scales linearly with its peak power, the cost per kWh will not directly depend much on the peak power of the charger. Instead, the main factor which influences the cost per kWh is the high utilization a charger has, i.e., the ratio between the energy a charger delivers in a year and the theoretical maximum energy it can deliver if it operates on full power 24 h per day, all days of the year. The long-term cost level for public fast charging is yet unclear, but as of 2025, there is a price level of about 0.4 EUR/kWh [26] or more for trucks. During the expansion phase of the charging infrastructure, it is likely that the competition will be weaker and the charger utilization lower than in a mature and stable market. Both these factors contribute to a rather high price. Therefore, it seems likely that the price may stay rather high during the ongoing expansion phase, to attract investors in a market with many uncertainties.

To have a similar or lower cost than diesel trucks, battery electric trucks should have a charging cost that, on average, is not higher than about 0.2 EUR/kWh (see Appendix B). There is a rather large uncertainty in this number, and rising diesel costs or CO_2-related fees can raise it. Given that it seems likely that most hauliers can reach an average cost level of about 0.2 EUR/kWh on their own chargers, that cost level is used as an upper limit for what, in this article, is called *low-cost charging*. Between 0.2 and 0.4 EUR/kWh is an intermediate cost level, in which chargers are cheaper than public charging but are likely too expensive to be the main charging source. It will be acceptable for some part of the energy to be charged at this cost, but it assumes that most of the charging will be cheaper than 0.2 EUR/kWh.

The total fixed cost for a charger, which is mainly investment in the grid connection, the monthly grid tariffs, and the price for the chargers, will vary roughly linearly with the peak power of the charger. For a given utilization of a charger, expressed, for example, as the number of full load hours the charger is used per year, the energy the charger delivers will also vary linearly with the charger power. The result is that the specific cost per kWh does not vary with charger power and the cost per kWh charged can thus be modelled with the charger utilization as the only important factor (see Appendix A). The modelled cost of a charger is shown in Figure 1 in which the red curve is the typical cost per kWh as a function of charger utilization. (The blue curve will be discussed later.) To make it easier to interpret the utilization from a haulier perspective, the charger utilization is not expressed in percent of the theoretical maximum, but rather as the number of full load hours the charger is used per weekday. This unit does not require that the charger is only used during weekdays, but it is expected that most hauliers have their main operations during weekdays. As an example, two hours of utilization per weekday means that the charger on average is used ten hours per week at full power, which corresponds to 6% utilization. The same two full load hours of utilization can, for example, also be achieved by using the charger for 15 h per week at two thirds of its peak power.

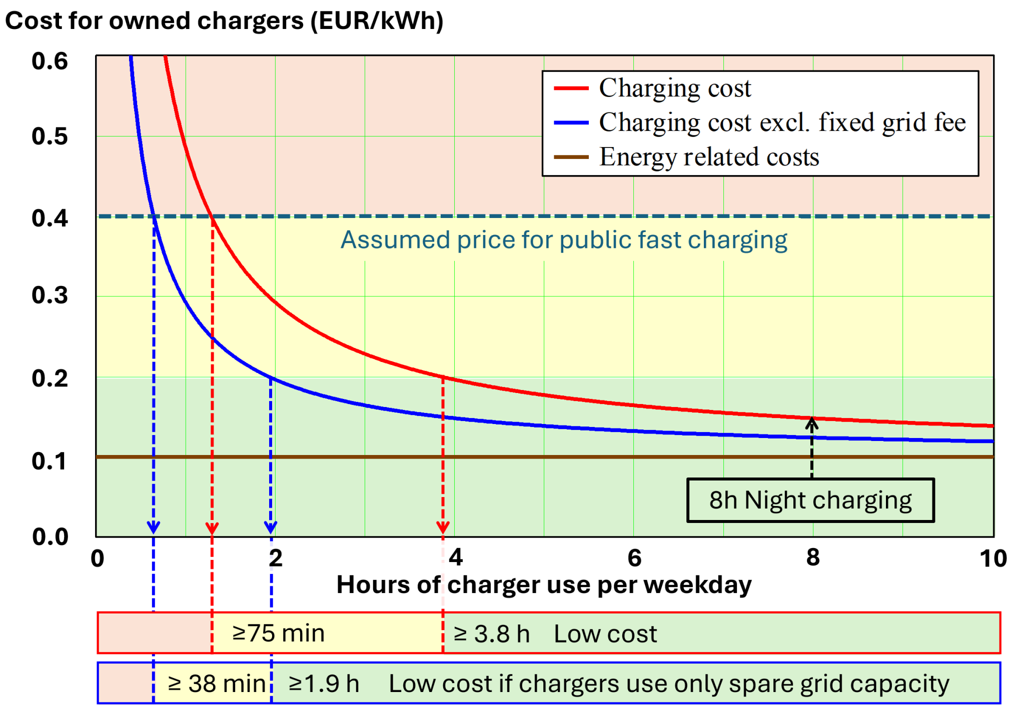

Figure 1. Costs per kWh for owned chargers as a function of utilization expressed as average full load hours per weekday.

The figure shows low-cost charging as a green band, medium cost charging as a yellow band, and expensive charging as a red band. The energy-related costs are independent of charger utilization and are shown as a horizontal brown line at 0.1 EUR/kWh (derived in Appendix A). The cost difference from that line up to the red line is the peak power-related costs, divided by the amount of energy charged. The diagram in Figure 1 can be used to determine which utilization is required to achieve a certain cost, or vice versa. It can be seen that a charger needs to be used for more than 75 min per weekday to achieve a cost of less than 0.4 EUR/kWh, i.e., lower than today's price level for public fast charging. It is necessary to exceed 3.8 h of use per weekday to result in a cost of less than 0.2 EUR/kWh. Night chargers that are utilized for 8 h per weekday result in a cost of 0.15 EUR/kWh. Significantly lower costs are unlikely, since the cost does not reduce much more if the utilization increases above 8 h, as the energy cost dominates at high utilization. To help interpret the significance of the charging cost, we note that an increase in average charging cost by 0.1 EUR/kWh is equivalent to the diesel price increasing by about 0.4 EUR/L, i.e., a substantial cost for the haulier.

2.3. Productivity

The productivity of electric trucks can be influenced by the charging strategy, for example, if the truck needs such a big battery that the payload must be reduced to avoid exceeding the maximum GVW. In those cases, a bigger and heavier battery will mean that the truck is allowed to carry less payload, reducing the income significantly. Most trucks rarely run on their GVW limit. For them, the amount of goods is instead limited by the volume of the goods, its floor footprint, or by how much goods the driver has time to handle during one shift. For all trucks which are not weight limited, the limit for possible battery size will mainly be how much batteries there is room for on the truck, and the battery weight will not influence productivity. For example, a diesel Volvo truck with 26 t GVW (FM 13 6 × 2 Tag Rigid with 4.9 m wheelbase) has a maximum payload of 18,285 kg, while a similar electric version with the same GVW (FM Battery Electric 6 × 2 Tag Rigid) has a payload of only 16,085 kg. If this type of truck is used for transports that have less than 16 t payload, the electric version will not have any reduction of pay load, while for heavy goods that require 18 t of payload, the reduction will be up to 2.2 t.

It seems that, in 2025, many trucks will offer batteries which in certification cycles have a driving range of 400 km and more, for example, Volvo FL Electric with a range up to 450 km or 515 km for a Scania with 42 t GVW. In real-world use, such batteries are suitable for driving up to about 300 km when planning with some safety margin. In this article, 300 km limit is used as a key factor when finding charging strategies. Up to that driving range, no charging is required. However, remember that it is not the exact number which is important, but it represents the maximum practical range for a truck which is not running at the allowed gross vehicle weight limit. When using the presented method, a haulier can therefore first analyse what the practical maximum driving range without charging is, for the type of trucks they use and their required payload. The 300 km range limit is just a suggestion for a default value that can be used in 2025, for non-weight-limited trucks. Since truck batteries continue to be offered in larger sizes, this limit can be expected to grow, and as the energy density of batteries slowly increases, the maximum range between charging for weight-limited trucks will also grow.

Productivity can also be reduced if the truck needs to stand still extra to charge during the workday, or if the truck needs to drive extra distance to reach a charger. So, a good charging strategy only requires the truck to charge when and where it parks for other reasons than charging, like between shifts or mandatory breaks. It should be stressed that for many trucks, if not most, it will be possible to find charging strategies that do not reduce productivity. In the following discussion, productivity reductions are not included. A reason for this is to get a clear discussion about the main differences between different charging strategies first. As a later step in the analysis of a specific case, any productivity consequences should be included. However, they will be very case-specific and are therefore difficult to include in a more generalized analysis like in this method.

2.4. Flexibility

Flexibility is a factor that influences short- and long-term profitability but is difficult to quantify. If it is easy for trucks to change from one type of transport task to another, it will help profitability in a way that may be important in the long run, but its value is difficult to estimate. A charging strategy that does not require the truck to charge during the workday will be more flexible than one that does, as the truck does not need to be at a charger at a specific time during the workday. Even if there is a need to charge during the workday, it is more flexible if the required charging can be at varying times and places rather than having to be done according to a very strict schedule. For fast chargers, high utilization occurs when many trucks share the same charger, leaving very little idle time between charging sessions. However, this reduces the flexibility of the trucks that rely on it. Thus, a fast charger with high utilization generally results in lower flexibility for the trucks than a similar charger with lower utilization. That means that there, unfortunately, is a link between lower cost achieved by using the chargers more and less flexibility.

2.5. Robustness

To be robust, a charging system shall be designed and used such that a failure of a single charger does not lead to large negative consequences. Similarly, delays in truck charging should not cause a chain reaction, where one delayed truck results in others also being delayed. One important factor that influences robustness is how many trucks share a charger. The fewer users of a charger, the less risk there is that a single problem causes significant problems for many trucks. A common way to ensure robustness is to have excess charger capacity at a site, which minimizes the impact if one charger fails. The cost of having two chargers when only one is required will be relatively high, while the cost of having six chargers when five are required is much more manageable. Therefore, it is often easier to achieve a more robust charging system if there are many similar chargers at the same site. Public chargers may play the role of backup for other chargers, and their existence may then increase the robustness of a system, even if they are normally not used. However, if a public charger is a necessary part of the charging strategy, it can also have robustness issues, as it cannot be guaranteed that it will be available exactly when needed, and, of course, it can also break down.

2.6. Business Risk

Business risks refer to the possibility of a commercial entity making inadequate profits or even losses due to uncertainties. Many charging strategies include the use of public chargers or chargers owned by another company. The availability and price for such chargers can change at short notice, without the haulier having the possibility to influence the situation. Depending on how important such a charger is, a change can be critical for the haulier's business. For business risk reasons, hauliers generally prefer a charging strategy based on chargers they own or control, rather than relying heavily on public chargers or those outside their control. Owning the chargers usually carries the lowest risk, but this is not always feasible or practical. In such cases, a long-term rental agreement can be a viable alternative. For example, if the haulier does not own the depot they use, the property owner may be the one owning the chargers, and they can be rented at a fixed monthly rent, just like the depot is rented. During early build-up phases, public chargers are associated with business risk. However, in a mature market, the business risk will most likely be reduced. The reason is that public charging, with many actors and strong competition, can involve very low business risk, similar to how reliance on fuel stations is not considered a risk for diesel trucks. Another solution is using chargers at a customer's location. They do not constitute a business risk if they are only needed to service that customer's transport and if access to them is a part of the contract for said transports. If they are also essential for fulfilling transport contracts with other customers and no easily accessible alternatives exist, they become a business risk.

2.7. Summary of the Operational Factors

The factors included in the cost–benefit analysis are summarised in Table 1 with short explanations and examples of their influence on the haulier.

Table 1. Factors in the cost–benefit analysis and their influence on hauliers.

Operational Factor	Why	Influence on Haulier
Charging cost	High fixed charger costs require high charger utilization for low charger cost/kWh	Chargers must be used about 3.8 h per weekday or more to be cost-effective.
Productivity	Productivity can be reduced by extra time used for charging, extra driving to reach a charger, or less payload due to heavy battery.	Charging should be planned where the truck stops anyway, and during breaks or when loading/unloading. Charging during workdays is a way to avoid batteries that are too heavy.
Flexibility	The need to charge during workdays requires the truck to be in a certain location at the right time.	The charging strategy must allow the truck to charge sufficiently even if it is delayed or had to change its plans, e.g., by offering alternate charging opportunities.
Robustness	Charging strategy must handle errors and disturbances without big negative consequences	There should be backup for all critical chargers, and there should be free charging slots which can be used if the planned charging did not work.
Business risk	It is important to secure access and price for chargers, which are critical for daily operation.	Owning all critical chargers, or renting on long-term contracts, secure access and price and allow the haulier to plan their use.

3. Results

In this section, the cost–benefit analysis method is applied, first to individual chargers, and thereafter, different charging strategies are ranked using it. Finally, a decision tree for selecting the charging strategy is developed. The decision tree is based on always suggesting the charging strategy with the highest ranking when it is possible to use it.

3.1. Evaluating Operational Factors for Different Types of Chargers

From a haulier perspective, there are important differences between chargers depending on how they are used and who owns them. To make the analysis easy to understand, the categorization should separate chargers based on how they influence the operational factors. In this method, the categories separate between charging during the workday and charging between workdays (called night charging). Charging between the workday has no direct influence on productivity and therefore can be slow and cost-effective. Charging during the workday has to be fast as it should preferably only be done during driver breaks to have no or a very minor effect on the truck's productivity. The chargers are also categorized regarding ownership as that influences business risk. The typical types of chargers investigated in this section are night chargers, fast chargers owned by the haulier, and public fast chargers. Not all possible charger categories are included as many of them are less attractive due to negatively influencing one or several operational factors. For example, fast night chargers have a high cost per charged kWh due to having an unnecessarily high power. Slow chargers for the workday are also excluded due to their negative influence on productivity. Public chargers are assumed not to be owned by the haulier, as they mainly serve many other users. For the owned fast chargers, three subcategories have been defined to show some of the main factors that influence their cost, robustness, and flexibility. Chargers at customers have been excluded from the analysis, as reliance on such chargers is a business risk and therefore should normally not be part of the basic charging strategy of a haulier. The results of this analysis are summarized at the end of the section in Figure 2.

	Own night charger	Own fast charger Using spare grid capacity	Own fast charger High utilization	Own fast charger Low utilization	Public fast charging
Typical cost (EUR/kWh)	0.15	0.2	0.2	0.4	0.4
Flexibility	Full	Changes moderately difficult	Changes to charging plan is difficult	Changes moderately difficult	Effect of changes not predictable
Robustness	One charger per truck. Disturbances limited	Disturbances spread to few trucks	Disturbances spread to many trucks	Disturbances spread to few trucks	OK if there are alternate chargers
Business risk	Low	Low	Low	Low	High
Ranking	1	2	3	3	4

Figure 2. Typical characteristics for different charger categories and their ranking.

For the charging strategies analysed, it has been deemed possible to only charge during the drivers' mandatory breaks, so the productivity will be the same for all the compared charging strategies and is therefore not included in the following discussion. This assumption is based on the fact that truck drivers in Europe must take a mandatory 45 min break after no more than 4.5 h of driving. The biggest truck battery sizes have now reached a level where the battery can last 4.5 h of driving at high speed and longer driving time at lower speeds, which means that the charging can be delayed until the mandatory driver break. The newest electric trucks are able to fast charge to an almost full battery in 45 min, especially the ones developed for the Megawatt Charging System (MCS). Big batteries and 45 min fast charging is expected to be offered in many electric trucks in the near future. Still, it is important to have productivity in mind when planning any charging during the workday, as it is a strong argument why charging should take place during driver breaks or when loading/unloading. So, despite not influencing our ranking directly, the productivity factor will put additional constraints on the scheduling of the trucks.

Figure 1 in the previous section can be used to determine at which utilization the cost per kWh is below a certain limit, and from that, it is possible to draw conclusions about the cost for different chargers. Note that the cost given by the red line is relevant for all chargers that the haulier owns, irrespective of whether they are low-power night chargers or fast chargers.

3.1.1. Own Night Charging

Charger cost: Night charging can be utilized about 8 h per night and is almost always the cheapest alternative, at a cost of about 0.15 EUR/kWh (as can be seen in Figure 1), i.e., below the 0.2 EUR/kWh limit mentioned above.

Flexibility: Since it should be possible to charge all trucks each night, there is typically one charger per truck; thus, there is no risk of the charger being occupied by another truck. With one charger per truck, there is no need to coordinate which truck charges when, making the system flexible.
Robustness: A system with one charger per truck is robust against variations in the trucks' schedules. There is, however, still some sensitivity to faulty chargers, but it is relatively low since only one truck is affected when a charger fails. There is also a greater possibility of charging that truck at another charger, as the charging does not need to be fit into a very short break in the middle of the workday. By having one more charger than trucks at a depot, there is also robustness against failures in a single charger.
Business risk: Night chargers should be owned by the haulier or rented on long-term contracts. Then they constitute a low business risk, as the haulier can rely on their availability, knows their cost, and has full control over how they are used.

3.1.2. Own Fast Chargers—High Utilization

Charger cost: According to the red cost curve in Figure 1, a fast charger can reach a cost of 0.2 EUR/kWh at a utilization of 3.8 full load hours per weekday.

Flexibility: Assuming the average charging time at the fast chargers is 30 min and most trucks only charge once per workday, about eight trucks must share one charger for it to be used more than 3.8 h per day. This means that the possible charging times for one truck are influenced by the seven other trucks using the same charger, which will significantly reduce flexibility when planning the schedules for those eight trucks compared to if they only used night charging. Assume the day-time charging is all done between 9 and 15. Then, 3.8 h of use means that the charger will be occupied 63% of that time period, i.e., if a truck unexpectedly needs to charge, there is only a 37% chance that the charger is free between 9 and 15.
Robustness: If a charger breaks down or a charging truck is delayed, more trucks risk disturbances the more trucks that share one charger. The robustness is therefore also low when charger utilization is high.
Business risk: Chargers owned by the haulier or rented on long-term contracts constitute a low business risk.

3.1.3. Own Fast Chargers—Low Utilization

Charger cost: To avoid flexibility and robustness issues caused by high utilization, it is possible to build more fast chargers for the same number of trucks, leading to lower utilization. However, that solution automatically results in a higher charger cost. If an owned fast charger is only used for 1.3 h, Figure 1 shows that the cost will become 0.4 EUR/kWh.

Flexibility: By building more chargers, the number of trucks sharing one charger can be reduced. A lower 1.3-h utilization will be possible with only three trucks sharing one charger. That is far better from a flexibility point of view, but still, the schedule of three trucks influences each other, which is still less flexible than only using night charging. Utilizing a charger for 1.3 h between 9 and 15 means that there is about an 80% chance of the charger being free at a random time between 9 and 15, which is much better than at high utilization.
Robustness: Just like flexibility, robustness is better for a fast charger that has low utilization, but worse than for night charging.
Business risk: Chargers owned by the haulier or rented under long-term contracts constitute a low business risk.

3.1.4. Own Fast Chargers—Using Spare Grid Capacity

If a premise already has a lot of night charging, the grid connection for the night chargers may largely be unused during the day. If that spare grid capacity is used for one or a few fast chargers that operate only during the day, when night chargers are idle, the addition of these fast chargers will not increase power-based grid fees. This eliminates roughly half of the fixed cost for the extra chargers, resulting in the cost shown by the blue curve in Figure 1. The blue curve includes the charger cost from the red curve but excludes all the grid costs, except for the energy transmission fees, which are already included in the 0.1 EUR/kWh energy costs.

Charger cost: Fast chargers using spare grid capacity only require 38 min of use per weekday to make them competitive with public fast chargers, and already at 1.9 h, they reach a low cost. Therefore, building fast chargers utilizing spare grid capacity will most likely be an interesting option for hauliers that have many night charging trucks.
Flexibility: As these chargers only need to be used by half as many trucks as fast chargers, which cannot use spare grid capacity, they will either be more flexible and/or have a lower cost than them. Still, night chargers will be more flexible and have a lower cost.
Robustness: Just like flexibility, robustness is generally better for fast chargers using spare grid capacity than for those that cannot, but worse than for night charging.
Business risk: Chargers owned by the haulier or rented on long-term contracts constitute a low business risk.

3.1.5. Public Fast Chargers

Charging cost: The current high-cost public charging is too expensive to be the main source of charging and can only compete with owned chargers if they have a utilization of less than 1.9 h per weekday.

Flexibility: Public chargers have the same compromise between availability and cost as other fast chargers, with the difference that the haulier does not control which vehicle should be allowed to use the charger at which time; therefore, using them becomes a gamble. A booking system may provide information about the availability of a public charger, but it does not reduce the need to match the transport plans with the charger availability, something that will still be easier if the haulier owns the chargers so that they control both scheduling of the transports and the scheduling of the chargers.
Robustness: Since there is no guarantee of the availability of an individual public charging station, the system is not robust if there is only one public charging station that can meet the charging demand of a truck. However, if there are several public charging stations that can meet the charging demand, without a need for driving extra distance to reach them, then robustness can be achieved by having redundant charger options. So early in the electrification, public chargers will often have a robustness issue, while in the long run, they may have sufficient redundancy if there are many stations to choose from.
Business risk: With public chargers, there is no long-term guarantee of their availability, their price, or how many queues they have. Thus, they pose a business risk.

3.1.6. Summary of Charger Analysis

Based on all the analysed factors, a pattern emerges for how to rank the different categories of chargers. Here, the ranking is discussed, and the outcome is summarized in Figure 2. Owned night chargers are, overall, the best, scoring highest in all compared factors. The second best is owned fast chargers, which can utilize spare capacity in the grid connection so that they do not increase the peak power-related grid costs. The third place goes to owned fast chargers that require their own grid connection. There are two versions of these chargers to illustrate the trade-off between either focusing on reducing cost, which requires high utilization and thus reduces flexibility and robustness, or flexibility and robustness, which require lower utilization and thus result in higher costs. Public chargers are, in many aspects, like owned fast chargers, but the business risk and the fact that the availability of the charger cannot be controlled by transport planners result in the lowest ranking of the investigated charger categories. Booking systems for public chargers may reduce the risk by showing if it is possible to charge a different time than planned. However, the haulier can still not rely on being able to reschedule charging to a new time, even if there is a booking system, since the booking system sometimes shows no suitable or available timeslots. In the future, once the market for public chargers is mature, they may compare more favourably with owned fast chargers, provided their price can be reduced significantly without problems related to charger queues.

A general observation from this discussion is the difficult compromise for fast chargers. Either they have high utilization, resulting in a low cost but poor flexibility and robustness, or low utilization with higher cost but better robustness and flexibility. The successful balancing of these conflicting goals lies very much in the details of how the breaks of the truck drivers can be spread throughout the day and if there are several alternative possibilities for a truck to charge, as that would improve robustness significantly. For hauliers that need to use fast charging during the workday, this will probably be a factor which requires much thought and creativity, and detailed analysis will likely pay off in lower costs and fewer disturbances. Some of the possibilities that should be explored are if the chargers can also be used over weekends, and if their use can be spread over more hours of the day, as that will increase utilization without increasing the risk of charger queue in the event of a disturbance.

The fact that several trucks must share a fast charger also means that they should only be built at places where there are many trucks that use them. Having just one fast charger at a site also makes the system sensitive to any error in that charger. Therefore, the charging strategy is more robust if there are two or more fast chargers at the same site. Thus, fast chargers for use during the workday require a minimum fleet size and should therefore mainly be built by hauliers or by depots with about 10 trucks or more that require daily fast charging.

3.2. Charging Strategies and Their Ranking

The ranking of charger types, presented in Figure 2, is made regarding how well they meet the operational factors in the cost–benefit analysis. Cost has been given a high weight since it is a prerequisite for a system to survive on a commercial market. The non-monetary factors, flexibility, robustness, and business risk, are judged subjectively and without a fixed weighting. Since they mostly point in a similar direction, their individual weighting is not critical to rank which charging strategy a haulier is likely to prefer over another.

3.2.1. (A) Only Using Own Chargers at Depot

The obvious charging strategy is to only use night charging since that is the best regarding all investigated operational factors. So, whenever that is a possibility, it should be the first alternative. For it to be possible, the trucks must return to the same depot after each workday, and it must be feasible to build chargers at that depot. A second condition for using only night charging is that it is possible to buy a big enough battery without reducing the payload of the truck. For trucks carrying loads that do not reach the limit for the GVW, driving up to about 300 km per day will be possible without charging. For trucks carrying heavier loads, the maximum driving range on a full battery is shorter, like 150–200 km.

One may ask if the high cost of a big battery is not a reason to add charging during the workday, even if that is not strictly necessary. Using a bigger battery when the daily driving distance is longer will result in the same battery cost per km as a smaller battery and shorter driving distance [27]. So, it is not more expensive to use a big battery, provided that it is used to drive a longer daily distance. Still, the battery cost may be reduced by charging during the day and using a smaller battery. However, it is unlikely that the resulting battery savings will be very high, so the cost for day chargers and lower flexibility when using them will most likely offset the advantage of a slightly lower battery cost. Still, in a more detailed analysis, that option should be explored to not miss-out on a possible reduction in the total cost.

Strategy A is called night charging because night is the time when the majority of such charging will occur, but it does not really matter much if the trucks are parked during day or night, if their usage pattern looks the same over a 24 h cycle. However, the terminology of night charging, workday, and day charging will be used and is based on the typical pattern of using trucks during the day and parking them overnight.

3.2.2. (B) Owned Chargers at Depot + Fast Charging at Own Premise

If it is not possible to use only night charging, what charging strategy will be the next option? Since night charging is normally the best option, it is still used during the night, but there is need for additional charging during the day. The best option will normally be to build their own fast chargers on their own premise, as they will normally be cheaper than public charging (in 2026), and the business risk will be lower. Strategy B requires that the trucks come back to the owned premise before driving 300 km after their previous charge. Since many trucks run in systems with a central hub, returning during the workday is common in the transport industry.

A long daily driving distance thus requires day charging. The reason for a long driving distance can be many hours of driving and few stops during a workday, but it can also be caused by the truck being used in two shifts. In the first case, charging will have to be during a driver break, while in the latter case, all or some of the day charging can be when the truck is parked between the two shifts. Two shifts normally reduce the number of hours the truck can be charged during the night to 4–6 h. That will reduce the utilization of the night chargers, but it is still high enough to result in a cost of 0.2 EUR/kWh or below.

3.2.3. (C) Owned Chargers at Depot + Public Fast Charging

If the truck does not return to the hauliers' own premises within the battery range, public charging or charging at a customer's location are the main options for charging during the day. The planning will be very similar to Strategy B, with the main difference being that the charger is not owned or controlled by the haulier; therefore, there is often uncertainty about its availability, and the price is normally higher than for an owned fast charger. That is the reason why Strategy B, with owned fast chargers, should always be considered first before turning to Strategy C with public chargers.

Why not add more than one charging occasion during the day in Strategy B and Strategy C to reduce the battery size and cost? That is a possible option, but also not a very likely way of making improvements. Adding more charging occasions during the day will allow for a smaller battery, but the truck must charge more times, which results in a much more complex planning of its schedule, and will make the use of the truck less flexible. The robustness will also drop significantly the more charging occasions that are necessary. Those drawbacks are likely to outweigh the reduction in battery cost. Still, there may be some special trucks that run very predictable schedules, often in industrial plants or mines, for which repetitive charging during the workday is a good option. But those are not within the scope of this article.

3.2.4. (D) Mainly Public Charging

Should the trucks not even return to the same depot each night, or it is impossible to build chargers there, they will need to fully rely on public charging. This can, for example, be long-haul trucks. The result will be high business risk, unless it is possible to secure access through long-term contracts. Even when that is the case, the charging price will typically be high. When all charging takes place on public chargers, the high price will result in high cost for operating the electric trucks. Consequently, it is normally not a good idea to start electrifying in this segment yet.

In the long run, there will most likely be fairly good solutions for those trucks as well but the challenges of starting in those segments during the early stages of electrification will be much more significant due to high cost and a high business risk.

3.3. Using Supplemental Public Charging in Rare Situations

The strategies above are defined to cover all the normal daily charging. It is very important that the cost for charging and the business risk are low, which means public charging is the last resort. Yet if a truck in rare situations needs to charge its battery more than usual and does so with supplemental public charging, a higher price and some extra time for charging are not critical, as long as it only constitutes a few percent of the overall energy used by the truck. If so, it will only make up a very small part of the charging costs, and there will not be any major business risk if a particular charger is not available or the price for public charging is raised. Of course, it is still important that public chargers exist to cover these needs, but it is not particularly crucial that they have a low price or that they do not require any extra breaks or extra driving, since they are rarely used.

3.4. Decision Tree for Charging Strategy

The previous reasoning about which charging strategies are preferred and under what conditions are summarized in the decision tree in Figure 3. It is built on the above ranking of the charging strategies and suggests Strategy A as long as it is possible given the biggest available batteries, and only when the driving distance during a workday is too long the decision tree suggests Strategy B, when that is possible, and then C. The decision tree illustrates that only a few factors need to be evaluated to find a suitable charging strategy. The main factors are:

- If the trucks always park at a depot that can have chargers;
- Daily driving distance (with a shorter threshold for heavy goods);
- If the truck returns to owned premises frequently enough to mainly charge there.

In the decision tree, there is also an extra question for capturing the few cases when it is possible to charge at the owned premise during the day, but public charging will still be more cost-effective. There can be several reasons for that. One is if there are too few trucks that can share the fast charger, since it will be expensive for the haulier to own such a charger. Even if there are several trucks, they still need to use the charger during different parts of the day, so a cost-effective owned fast charger is only possible in a system in which the trucks are not synchronized but return to the premises at different times. Despite these possible reasons to use public charging, for most hauliers with several trucks that need charging during the day, it is believed that owned fast chargers will be a better choice than relying on public charging daily. Answering "No" to the question of whether one's own fast chargers are more cost-effective than public charging will, during the early phases of electrification, often mean that it is better to wait to electrify those trucks.

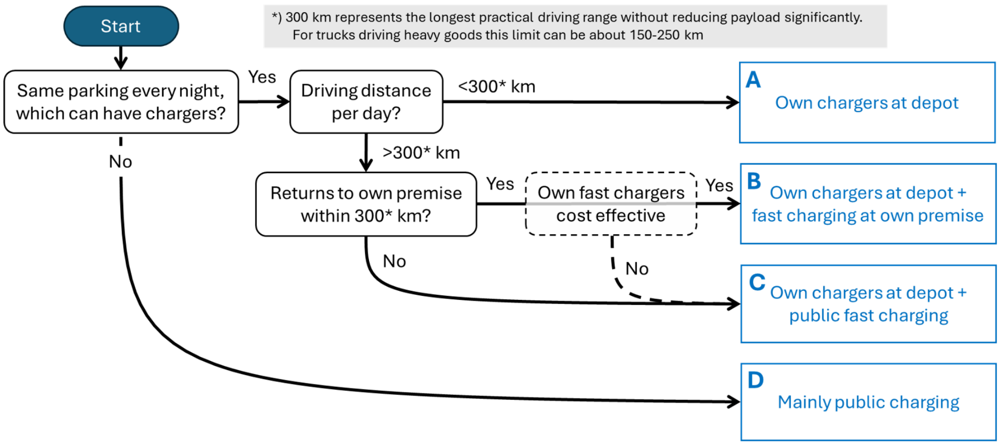

Figure 3. Decision tree for finding a suitable charging strategy for trucks.

4. Discussion

In this article, a simplified method to analyse what charging strategy is suitable for different trucks is introduced. It is not intended to manage all details, as that would result in a far too complex method, and on purpose, it only focuses on some strategies that are likely good candidates for most trucks in the near future to make it easy to use for practitioners.

4.1. Decision Tree and How It Can Be Used

The decision tree is intended to be the first step in analysing how a specific truck fleet can be electrified. It suggests a charging strategy that can be the starting point for a deeper analysis once a haulier decides that electric trucks are of interest to them. The cost–benefit analysis in this article will also help decide what factors to include in a more detailed study and how to interpret the results.

By making the method very simple, people who are not experts in electrification but are professionals in the transport industry will understand it so well that they can combine it with their own expertise to draw more trustworthy conclusions about their own trucks than any general model can. The decision tree has been tested in dialogue with hauliers within the projects REEL 2 and E-charge, and the tests have shown the method to be effective in quickly providing an overview of different options and guiding the discussion towards factors that are important for the hauliers.

4.2. What the Decision Tree Says About Charging Strategies and Electrification

Since the building of public charging is typically not done by hauliers themselves, it is important to know how much public charging is required for a truck fleet before deciding to electrify it. It is often said by hauliers that they need to wait for public charging to become abundant before they can start electrifying their fleet. The decision tree can help them identify if they actually need public charging and to what extent. The cost–benefit analysis shows that solutions without public charging are the main options and that there are many categories of trucks that can do without any regular use of public chargers. Thus, the analysis method may prevent hauliers from unnecessarily waiting for a build-out of public chargers, which they may later find they do not need.

4.3. Results About Chargers

The main finding from the cost–benefit analysis is that night charging is the best solution regarding all the compared operational factors. Therefore, fast chargers will mainly be used to supplement the charging that cannot be obtained during the night due to limits in battery size. The main problem with fast chargers is that they are shared by many trucks, which creates a conflict between low cost versus flexibility and robustness. The main challenge is, therefore, where to build fast chargers and how to plan their use so that they have a high utilization without resulting in inflexible schedules and robustness issues. This puzzle will depend much on the details of how the trucks are used and is therefore not possible to give a generic answer to. One way to make this compromise easier is if the charging can be spread over many hours of the day, as that allows for higher utilization and/or a lower risk of queues.

Utilizing a grid connection used for night chargers also for a few fast chargers will allow the fast chargers to be added without any extra cost for the grid connection, provided the fast chargers are only used when the night chargers are not, and the total peak power of the fast chargers is lower than the total peak power of the night chargers. Generally, chargers that can use existing grid capacity can achieve a low cost for charging already after about 1.9 h of use per weekday. Already at 38 min of use per weekday, such chargers will be cheaper than the present (2026) price for public charging.

Public fast chargers fall short due to their current high price, which makes them the last resort. On top of that, they are a business risk, at least until a very mature and well-developed public charging network is in place. This is why public chargers will not be a competitor for the majority of the charging for commercial trucks. Rather, they will initially mainly be a rarely used supplement in the event of failures or changes to the truck's schedule.

To compete for normal daily charging, public fast chargers must have a low price, be available where the trucks need them, and have a low risk of queues. That may very well be a possible situation in the future, but it is unlikely to be the case during the initial transition from diesel trucks to electric trucks.

4.4. Sensitivity to Parameters and Assumptions

The differences in cost per kWh for different chargers are not sensitive to the cost parameters, as all chargers have similar specific costs per kW of peak power. Thus, it is the difference in how many hours they are used that determines the ranking in cost. However, the trade-off between low cost OR flexibility and robustness will be influenced some by cost parameters. A much lower cost level for chargers will reduce how many hours a charger must be utilized, making the problem of robustness and flexibility smaller. However, the costs will have to be several times lower than assumed for the flexibility and robustness problem to become unimportant.

The assumed 300 km range limit for how long a truck can be planned to drive without charging is not critical for the method or the conclusions. The value is just a rough example of where this limit is in 2025. The method works as well with other values of this limit, and each user should check what the limit is for their own trucks before using the method. An increased value just makes more trucks end up in the case where night charging only is the best option, making electrification easier than if they require charging during the workday.

4.5. Limitations

The analysis method has been developed based on reoccurring themes in the current literature and researchers' expertise about the operation in today's transport system and combining that with knowledge about the technical possibilities and economics of electric vehicle systems. It is believed that it captures many of the most important factors influencing what is a good charging strategy for electric trucks. The authors are aware that there may be other operational factors that could be relevant to include and other ways of defining charging strategies that will provide different insights into which charging strategy is good. One simplification made in relation to operational factors was the decision not to include productivity when evaluating charging strategies. This decision was based on the assumption that productivity is unaffected if charging occurs during the driver's mandatory breaks. While this is correct, productivity may also be influenced by a loss of payload due to heavy batteries or by reduced flexibility in scheduling.

The purpose of this method is not to capture all factors which can influence which charging strategy should be used, as that would make the method complex and unusable for practitioners. Rather, the paper aims to explain some charging-related factors that are vital for a good system design, and to present them in a framework that is easy to understand such that practitioners can combine this knowledge with other factors when deciding which charging strategy to use. Therefore, it is recommended that experts and practitioners should combine and compare the results of this method to what they know from other viewpoints before making decisions based on the results from the presented method. Some factors that have been excluded are variations in energy prices, over and between days, and variations in battery cost and battery ageing between different charging strategies.

This framework assumes that it is possible to build chargers where and when they are needed, which is of course often not the case. The method can therefore on its own not tell which is the right charging strategy, but it points towards what would be a good long-term solution. Knowing a good long term goal is a necessary basis for making good compromises here and now. Without understanding the long-term consequences, there is a risk that short-term problems lead a haulier on a path to a system which is not good in the long term.

5. Conclusions and Implications

Electrification of freight trucks is a challenging task, and this perspective article approaches this using a systems perspective with the aim of exploring the connection between charging strategies and operational factors. As a first step, five operational factors were identified as important for performing a cost–benefit analysis: charging cost, productivity, flexibility, robustness, and business risk. By linking these factors to different types of chargers, the results show that focusing primarily on charging costs and not on the other factors may lead to the wrong conclusion about which type of charger should be preferred. To take it one step further, the results have been operationalized and adapted to charging strategies to highlight which charging strategies should be preferred depending on the trucks driving characteristics. The results show that charging strategies that entail owned chargers (by hauliers) should be prioritized. The results also suggest that many hauliers can solve most, if not all, of their charging needs themselves. It is therefore likely that many can start electrifying soon since public charging is often not critical for the electrification of their trucks.

Regarding contribution to research, this article contributes to an increased understanding of how charging strategies can be evaluated by using five operational factors. These results contribute to the electrification literature in general and particularly provide insights for studies that have highlighted this as challenging [11,19].

This article has important implications for practice in several ways. First, a decision tree is suggested that considers where the trucks are parked, the daily driving distance, and whether the trucks return to owned premises during the workday. This decision tree can function to create an understanding of which charging strategies fit different distribution routes.

Second, since the method is necessarily simplified, it is also vital that the hauliers understand which factors are important to analyse when deciding on the charging strategy and how those factors link to the cost for charging. Therefore, the article also explains a cost–benefit analysis of a few operational factors and how they are influenced by the charging strategy, such that hauliers shall be capable of using this method in their own analysis and combining it with their expertise in transport and business.

Third, for fast chargers, there is a difficult compromise between low cost OR flexibility that is present both for chargers owned by the haulier and public chargers. Innovative ways of balancing the opposing goals effectively are likely the key to high profits from electric trucks. The main challenge for the haulier is to decide where to build chargers and how many, and then plan the trucks' charging schedules with high charger utilization, flexibility, and robustness in mind. Selecting the right charging strategy may often be more critical for business success than saving on battery costs by reducing the battery size.

The operational factors have mainly been evaluated using qualitative analysis, based on the researchers experience and expertise. Thus, the ranking of the operational factors should be viewed as a starting point, but open for future research to develop alternative approaches for their evaluation, such as testing the method on real fleet cases or employing quantitative measures or methods (such as analytical hierarchy process). Such methods could be used both to validate the operational factors and to assess how each factor is operationalized (i.e., the ranking of different charging strategies). Furthermore, the decision tree is a good way to start when analysing how to electrify, since it provides an overview of how different driving characteristics match different charging strategies. As a next step, future research could validate the method by testing it on real cases and determining how the method can be developed. Moreover, given that the method and decision tree focus on specific routes and hauliers that rely on their own depots for charging (for Strategies A, B, and C), future research could examine how the method could be developed to address a more integrated transport system that incorporates, for example, shared hubs, or how the operational factors are affected when hauliers employ subcontractors. Lastly, five operational factors were identified as relevant; however, there could also be other factors. One example is the cost of batteries, since a change in the charging strategy could result in a change in the required battery size and thereby cost. In cases where two different charging strategies are both similar regarding the other criteria, the battery sizing and cost could influence the choice of charging strategy. Furthermore, the method used applies a simplified measure of productivity that considers where the trucks stop to charge and the range limitation, aiming to avoid loss of payload caused by the additional battery weight. The significance of productivity is an aspect that future studies could address.

Author Contributions: Conceptualization, A.G. and H.G.; methodology, A.G.; investigation, A.G. and H.G.; writing—original draft preparation, A.G. and H.G.; writing—review and editing, A.G. and H.G. All authors have read and agreed to the published version of the manuscript.

Funding: This research and the APC was funded by FFI, Strategic Vehicle Research and Innovation, grant numbers dnr-2021-03845 and dnr-2024-03622.

Data Availability Statement: The data supporting the findings of this study are available within the article and Appendices A and B.

Acknowledgments: The dialogue with, and information from, the companies and organizations within the projects REEL and E-Charge is gratefully acknowledged.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

GVW Gross Vehicle Weight

Appendix A. Charger Costs

The cost for a charger can be divided into the following main parts, based on how they vary with key parameters:

- Depreciation and capital cost for the investments in chargers and grid connection. These costs are paid when building the station and vary roughly linearly with the peak power of the chargers.
- A monthly grid fee depending on the maximum power (one hour average) of the charging station. This cost also varies roughly linearly with the peak power of the chargers and is the same irrespective of the amount of energy charged.
- Costs for the energy, including energy-related grid transmission fees and energy tax, which are proportional to the energy charged.

For chargers that a haulier builds on their own premise and where the vehicles anyway would park, there is little cost for additional space for the charger, so that is not included in this cost model.

In 2024, the energy tax in Sweden is 0.428 SEK/kWh [28], which translates to 0.038 EUR/kWh, and a typical grid transmission fee is about 0.007 EUR/kWh. The energy price is set on an energy market, Nordpool, and varies from hour to hour based on supply and demand. In 2024, it was on average 0.036 EUR/kWh in the middle region of Sweden (SE3) and 0.050 EUR/kWh in the south region of Sweden (SE4) [29]. However, the average price for a charger will depend on which hours during the day the electricity is bought, and therefore a little higher price of 0.055 EUR/kWh is used. This results in a total energy-related cost of 0.10 EUR/kWh.

Since a charging station typically has some hours each month when it is used to its full capacity, it is assumed that costs for the investments and the grid fee both depend on the peak power of the charger(s) so that they can be combined into one fixed monthly cost proportional to the peak power of the chargers. In Sweden in 2024, the fixed cost for chargers and grid is about 100 EUR/kW/yr, of which roughly half is the investment cost and the other half is monthly grid fees.

To estimate how charger costs influence the TCO for a truck, the total cost for a charger is determined per kilowatt hour the chargers deliver. The cost component, which varies with peak power, can be translated into a cost per kWh if the utilization of the charger is known, i.e., the ratio between energy charged per year divided by the theoretical maximum energy that can be charged during a year (i.e., when the charger is running at peak power day and night for 365 days). First, one calculates the cost per kWh at maximum (100%) utilization

$$c_{\mathrm{MaxUtil}} = 100\ \mathrm{EUR}/(\mathrm{kW} \cdot \mathrm{yr}) = 100\ \mathrm{EUR}/(\mathrm{kW} \cdot 8760\ \mathrm{h}) = 0.0114\ \mathrm{EUR}/\mathrm{kWh} \tag{A1}$$

The total cost per kWh of charged energy can be calculated as function of the actual utilization

$$c_{\mathrm{Chg}}(k_{\mathrm{util}}) = \frac{c_{\mathrm{MaxUtil}}}{k_{\mathrm{util}}} + c_{\mathrm{Energy}} \tag{A2}$$

Using a charger for $T_{\mathrm{utilWeekday}}$ hours each weekday, 52 weeks per year, results in a utilization time of

$$k_{\mathrm{util}}(T_{\mathrm{utilWeekday}}) = \frac{T_{\mathrm{utilWeekday}} \cdot 5\ \mathrm{day/week} \cdot 52\ \mathrm{week/yr}}{8760\ \mathrm{h/yr}} \tag{A3}$$

Equation (A2) is plotted as the red line in Figure 1 with the utilization on the x-axis defined as in (A3). Note that the cost, after some minor simplifications, does not vary with the size of the charger. So, this cost estimate can be used for all chargers that are used only by the haulier. For public chargers, the same cost model applies; however, there is a need to add a profit margin, and it is not certain that the costs are split evenly on all the charged energy.

Appendix B. Acceptable Charging Cost

To be able to judge what is an acceptable cost for different chargers, a cost reference for truck types which compete with battery electric trucks is needed. Currently (in 2025), the primary competition will be diesel trucks. Most of the cost will be roughly the same for diesel trucks and electric trucks, and only the costs that are not equal need to be compared to find what is a reasonable cost for charging.

Without its battery, an electric truck will cost about the same as a diesel truck. Before electric trucks are mature, their maintenance and insurance are assumed to cost the same as diesel trucks, and they are expected to operate the same total driving distance during their service life. If charging only takes time between shifts or on existing breaks, the driver cost will also be equal since no extra cost for drivers is needed during charging. All those cost categories being roughly equal leaves only the cost for diesel fuel to be compared with the cost for the battery, chargers, and the electric energy.

A typical European 40 tonne truck consumes about 35 litre per 100 km. At a diesel price of about 1.2 EUR/L (excluding VAT), this results in a diesel cost of 42 EUR/100 km. An equivalent electric truck consumes about 140 kWh/100 km, which means that the corresponding cost for the electric truck can be at most 0.3 EUR/kWh if it shall be cost-competitive with a diesel truck.

One part of the 0.3 EUR/kWh must pay for the battery. A way of estimating the cost of a battery, per kWh energy it delivers, is to divide the cost of buying the battery by the energy it is expected to deliver during its service life [27]. Batteries are assumed to be priced at around 200 EUR/kWh for the truck buyer (i.e., not the cost to produce the cells). In commercially used heavy trucks, the battery is expected to last about 2000 equivalent full cycles or more, and then the battery cost is 0.1 EUR per/kWh it has delivered. A battery cost of 0.1 EUR/kWh leaves 0.2 EUR/kWh to pay for the chargers and the electric energy combined, i.e., the cost calculated by Equation (A2).

There are of course many uncertainties in the estimated costs. Lower battery cost, lower maintenance cost, or longer service life of electric trucks will allow for more expensive charging, as will a higher diesel price or extra road tax on diesel trucks. Despite the uncertainty in the costs, it is, in 2025, realistic to classify a cost for charging of 0.2 EUR/kWh or less as a low cost for charging, as it can make many battery electric trucks cost-competitive with diesel trucks. It is also clear that a cost of 0.4 EUR/kWh or more is high, as it is significantly higher than the cost of diesel fuel, even without adding the cost for the battery, and, therefore, will make a battery electric truck significantly more expensive than diesel trucks.

Note that 0.2 EUR/kWh is a limit for the average cost for all the energy charged by a battery electric truck. Some small part of the energy may cost much more to charge, as long as it is compensated for by much of the energy costing less than 0.2 EUR/kWh.

This appendix has shown that the average charging cost, including the cost for the charger and energy, should stay below about 0.2 EUR/kWh to be competitive with today's (2026) diesel trucks without any special subsidies. Even if the diesel trucks become more expensive and/or the electric trucks become cheaper to operate, there will still be a need to select charging strategies that lead to a low cost, so it will still be relevant to strive for a charging cost of 0.2 EUR/kWh or lower.

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