energies

MDPI

Article

Charging and Discharging Scheduling for Electrical Vehicles Using a Shapley-Value Approach †

Marija Zima-Bockarjova [1], Antans Sauhats [2], Lubov Petrichenko [2,]* and Roman Petrichenko [2]

1 ABB Corporate Research Center, 5405 Baden-Dättwil, Switzerland; bockarjova@gmail.com
2 Institute of Power Engineering, Riga Technical University (RTU), LV-1658 Riga, Latvia; sauhatas@eef.rtu.lv (A.S.); romans.petricenko@rtu.lv (R.P.)
* Correspondence: lubova.petricenko@rtu.lv; Tel.: +371-283-07-721

† This study is an extension of the paper "Shapley-Value-Based Charging and Discharging Scheduling for Electric Vehicles in a Parking Station" presented to 2019 IEEE 60th International Scientific Conference on Power and Electrical Engineering of Riga Technical University (RTUCON), Riga, Latvia, 7–9 October 2019, and published in the Conference Proceedings (DOI:10.1109/RTUCON48111.2019.8982376).

Received: 21 February 2020; Accepted: 1 March 2020; Published: 4 March 2020

check for updates

Abstract: The number of electric vehicles (EV) in the world has been increasing and is gaining momentum. The large-scale use of EVs in public life has initiated the need to establish EV battery charging services within the power system. Currently, EVs serve as a transportation tool and also as a flexible load. This publication examines the possibility of the owner of an electric vehicle choosing a battery recharging point, as well as of the involvement of several decision makers in the selection of a charging schedule. This problem is important because we assume that a significant proportion of EVs mainly use two parking spaces, one located close to the place of residence and another close to the workplace. We accept and prove that a car charging station can be created by the employer (company) and implemented in the best interests of the employer and the employee (EV owner). For that, a coalition between the company and the EV owner has to be formed. To support rational decisions, this study solves the problem using the cooperative game theory and designs a payment distribution mechanism based on the Shapley value. The results obtained prove that the coalition is beneficial under different conditions, which depend on the capacity of the EV, the distance between the workplace and the place of residence, the difference in the electricity prices of the day, as well as the consumption of the company. In order to estimate the coalition's gain, it is necessary to take into account the structure of the power tariff system for both the company and the EV owner. Furthermore, we prove that the presence of a coalition allows the company and the EV owner to reduce the annual fee for consumed power. The results of this analysis could be adopted by decision makers such as government agencies, companies, EV owners, and they are recommended for potential investors for the development of transport electrification and smart energy.

Keywords: electric vehicles; Shapley value; battery charging; optimization; coalition

1. Introduction

The gross consumption of renewables gradually rises every year. The installed capacity amount of world renewable energy increased overall by 52.0% between 2009 and 2018 [1]. The use of renewable energy sources is an important and necessary step towards limiting greenhouse gas emissions and partially promoting transport electrification [2–8].

In various countries, a sharp growth in the number of electric vehicles (EV) is observed. The automotive industry is seriously investing in the development of fully electric vehicles and hybrid electric vehicles. In 2018, the global electric car fleet exceeded 5.1 million, an increase of two million from the previous year [9]. Due to the expected large-scale expansion of EV into the system, there is a need for vehicle battery charging services [10,11].

An EV, as a consumer of electricity, acts as an energy storage system (store energy and even give it to the power grid) [11–14] and also as an electrical load. Moreover, it is able to select the point of network connection and the schedule of the charge/discharge process. These features of EVs in the context of the growing use of renewable and very volatile energy sources attract particular interest, as they provide a balance of consumed and generated energy. Additionally, freedom to choose a consumption schedule for EVs offers regulation services and consumption flexibility that can be used to solve a number of other important tasks [15] of the power grid and the system. Note that the EV can only be used as a storage and balancing device when parked. However, this restriction is not vital for most EVs, since they spend, on average, more than 90% of their time parked [10].

Electricity retail tariffs with time-varying prices enable consumers to minimize expenses by using electricity from the grid during hours of its lowest cost. This determines an increasing interest in energy storage technologies, from which, EVs are considered among the most promising ones [2]. EVs can be connected behind consumers' meters, and therefore they can use this system at their own discretion, without coordination with the power grid operators. A desire to reduce energy costs requires solutions to a number of tasks which include: choosing an electricity retailer, selecting control algorithms from a wide set of options with varying complexity, forecasting prices, developing optimization, and verification algorithms [3].

The spread of EVs is impossible without the creation of a network of parking stations which provide the ability to charge EVs. It is important that the EV can act as a load or a distributed storage device during the parking time in order to maximize benefits to the power system and the EV owner. To further accelerate the process of electrification of cars, it is necessary to use the new functions, integrate them into the network, and maintain rational control of the charging/discharging process.

A significant number of studies have been conducted to understand the opportunities and challenges associated with the widespread deployment of EVs [10,15]. For example, the authors of [10,16] focused on finding ways to integrate EVs into smart grids. The authors of articles [16–21] described energy management systems for smart charging stations. These systems are built following the aims of the distribution system operator and considering various types of EV battery charging technologies, charging time restrictions, and other technical limitations.

A number of studies underline the importance to analyze EV users' charging habits, preferences, and opportunities to evaluate the beneficial charge and discharge time of the EV for the user and for the network [17–20]. A study by [20] suggested a method which was focused on EV users' benefits that decreased the cost of battery capacity degradation, electricity cost, and waiting time for different situations. Taking into account the EV users' travel habits, a model of the EV aggregation was developed in [17] to define the real-time available vehicle-to-grid capacity during an entire day. The authors in [19] presented a method for the optimization of daily activity chains of EV travelers, using the genetic algorithm structure to estimate a suitable schedule of activities. Two charging scenarios were implemented. In the first case, the EV owner stayed at the charging station, and in the second case, he charged the EV at the charging station while conducting another activity at a nearby location. The authors of [16,19] described in detail the EV users' traveling habits and EV implementation in a home system. Analyzing the research results [16–20], we conclude that various EV traveling routes are classified into two types, regular routes (home/work/home) and irregular routes (home shops/hospital/social events/etc.). A number of studies have solved the problem of optimizing EV charging processes [8,10] by using detailed models of battery charge and discharge procedures; some models are relevant for cases with time-of-use tariffs (peak, mid-peak, and off-peak prices) [15]. The division of prices into several zones significantly simplifies the task because the prices are known well in advance and it is possible to use a deterministic approach and linear programming. However, the greatest gain from the use of batteries is possible with tariffs that depend on the wholesale market price of electricity, which is different for each hour, i.e., real-time pricing. The possibility of choosing dynamic tariffs based on wholesale market prices is provided in many countries [20]. Unfortunately, time-of-use tariff-oriented methodologies cannot be applied in cases of hourly (or even more detailed) price changes. Under these conditions, the task at hand is much more complex [10]. Systemic reviews of energy storage system optimal control problems and their solution approaches are given in [21,22]. There are two main families of optimization approaches. In the first approach, standard formulations of an optimal control problem use a deterministic model, where it is assumed that the state of the system in question can be set for the entire planning period. In the second approach, in a more general and complex case, researchers take into account the uncertainty that inevitably arises from the need to forecast the state of the system in the future. If uncertainty is taken into account, in most cases, a two-stage problem of stochastic programming is posed and solved [22]. The author of [21] claimed that optimization-based approaches are frequently proposed for the control of EV charging; however, they were simplified with several assumptions and were not compared to simpler approaches. As a result, the author compared optimization-based approaches with rule-based approaches in a realistic scenario, in which a certain limit for the total load had to be satisfied.

A significant number of publications [23–29] analyzed the formation of coalitions of several players (decision makers). Reference [23] focused on the penetration of plug-in hybrid electric vehicles (PHEVs) and its impact on the distribution grid. In the article, it was pointed out that using cooperation among PHEVs and the grid effectively stimulated PHEV users to charge in the load valley and discharge at peak load; it was concluded that a PHEV coalition is a win–win strategy for both the PHEV users and the grid. In [24], the concept of cooperative EV-to-EV charging is presented. In this case, the EV acts as both an energy provider and a consumer. A flexible energy management protocol with various algorithms for the above-mentioned cooperation is developed. A coalition which included a photovoltaic system and an EV charging station was considered in [25]. The authors proposed a multiparty energy management for an EV charging station cooperating with a photovoltaic plant in a smart grid. The research used a profit-sharing method which was based on cooperative game theory. Simulation tests showed that in cooperation mode a profit growth trend was observed for each subject of the coalition. Another alliance of three players, i.e., wind power, thermal power and EVs was proposed in [26]. Three scheduling models of the alliance were presented for maximizing the profit of the cooperation. The Shapley value (ShV) and other methods for the fair distribution of the profit of the tripartite coalition were used. Unlike the above articles, reference [27] addressed a static non-cooperative game formulation of the problem of distributed charging in EV systems. Two versions of charging games were proposed. In both scenarios, equilibrium analysis was used. A view of a cooperative game and an investigation of the cooperation of three players, i.e., the grid, a gas station, and a car park was presented in [28]. Five possible coalitions of the profit model were simulated, and the best case was found in which the three-party alliance could be proven. The ShV approach was used to obtain the fair distribution of the coalition's additional gain.

In summary, on the basis of the results of the publications devoted to EV smart charging control, we conclude that there is a large number of ways and algorithms to solve this problem. Detailed models of optimal control and effective algorithms for finding optimal solutions of EV charge processes have been developed and tested. In particular, the following have been proposed: An EV optimal charging method that could improve the gain of charging facilities, an EV optimal charging method that could reduce the charging costs for the users, an algorithm that provides a profitable network operation mode, and methods of forming coalitions that can provide additional benefits to their members. At the same time, the possibility of forming a coalition between the owners of EVs serving one company and the owners of this company remains unexplored. Such a statement of the problem is important because we assume that a significant number of EVs mainly use two parking spaces [16,30] as follows:

1. At the place of residence (PR) of the owner of the electric vehicle;
2. At the place of work (PW) of the EV owner.

We assume that all parking places are equipped with battery charge systems and we believe that these places are approximately equivalent in terms of user comfort. At the same time, the rules of billing at different sites can be diverse, partially because EVs are parked at a PR in the evening and at night, but in the morning and during the day, most EVs are parked at a PW. The technical capabilities of charging stations can vary. The EV owner can choose the location and the schedule for charging or discharging the batteries, and we assume that the owner seeks to minimize the cost of energy used. However, this cost not only depends on the choice made by the owner of the EV. It is influenced by the decisions taken by the owners of the companies' charging stations, who also seek to gain.

The freedom of choice of the location and schedule for charging and discharging an electric vehicle can provide a reduction in the cost of the energy consumed. To achieve this, it is necessary to change the formulation and solution of the optimal control problem. The main feature of the revised task is the presence of a coalition which includes two or more actors who pursue different goals and decide among optimization variables. The presence of several actors leads to the need to find a solution to the problem using elements of the game theory.

The main contributions of this study are summarized as follows:

1. The possibility and the rationality of forming a coalition of the owners of electric vehicles serving the same company and the owners of this company are investigated;
2. The tasks of maximizing and distributing the additional gain of the coalition are posed and, based on the use of the Shapley value, they are solved;
3. On the basis of the analysis of the billing system of various countries, we offer a generalized structure of the billing system using proportionality coefficients;
4. The effectiveness of the proposed approach is shown on the basis of the collected data (the electrical load, the dynamic prices of electricity, the technical parameters of the electric vehicle and the usual route).

The rest of the article is organized as follows: Section 2 describes the essence of problem; Section 3 is devoted to the statement of the control optimization problem, to the description of the methodology, models, constraints, the current billing system's rules; Section 4 contains a description of the initial data and assumptions and it also reflects the results of the calculation of minimizing coalition costs; and the last sections are devoted to discussions and conclusions.

2. The Essence of the Problem

Let us look at the important behavioral traits of many owners of electric vehicles which follows from the fact that most of them are employees of various companies (industrial enterprises, educational institutions, shopping centers, etc.). Employees spend much of their time at the workplace. Most of the remaining time is spent at the place of residence. Let us assume that the company, i.e., the employer (hereinafter referred to as the company) has a parking lot intended for its employees and equipped with a car charging/discharging station. The presence of such a station allows the company not only to ensure the comfort of the employees, but also to use the batteries of their EVs to control power consumption. We assume that the duration of the working day is set and that during this time the employees' cars are parked. A simplified diagram of the situation is presented in Figure 1.

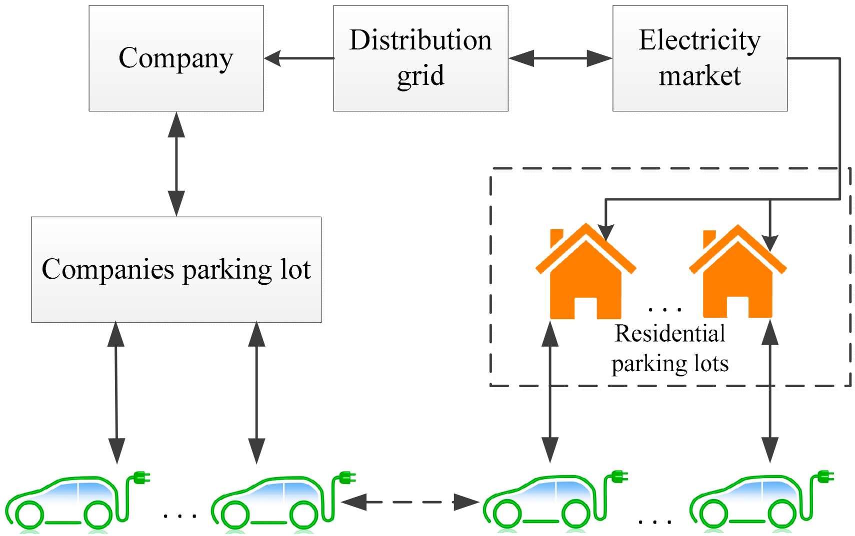

Figure 1. The diagram of the situation under consideration.

In general, energy consumers can be equipped with bidirectional converters. However, in this article we assume that the company's stations are equipped with converters that provide only battery discharge, and car owners only have the option of charging batteries at their place of residence. We accept that energy supply processes are governed by the following rules: (1) the day-ahead electricity market [31] and (2) the energy billing system [32]. Electricity consumers use smart meters and dynamic tariffs, and therefore must consider hourly price changes. We also accept that the consumers depicted in Figure 1. do not influence the prices of the electricity market and assume that the company and all N_{EV} users of the parking lot are striving to obtain an advantageous charging/discharging process of the EVs and for this purpose coordinated actions of the company and the N_{EV} users of the parking lots are necessary. Creating a coalition necessitates the consent of all the potential participants. To form a coalition, one needs the following: A tool to manage the behavior of the coalition members, a tool to estimate the benefits and the economic efficiency of the coalition, and a methodology and a tool for sharing the benefits of the coalition among the participants. Meeting these requirements is the primary purpose of this article.

3. The Statement of the Control Optimization Problem

3.1. Objective Functions, Variables, and Constraints

A tool for managing the behavior of coalition members is created on the basis of setting and solving the optimal control problem [28]. Before considering the optimization of the actions of a possible coalition, we describe the objectives of individual participants in its absence.

Acting independently, in the absence of EV parking for employees, the company seeks to minimize the cost of the energy consumed:

$$C_{comp}^{T_{pl}*} = \sum_{t=1}^{T_{pl}} (C_{Comp}^{t}) \rightarrow min, \forall\, t \in T_{pl} \quad (1)$$

where T_{pl} is the number of sampling steps Δt (e.g., one hour) in the planning period of optimization, C_{Comp}^{t} is the cost of the energy consumed by the company during hour number t, and $C_{comp}^{T_{pl}*}$ is the minimized cost of energy consumed by the company during the planning period. The cost $C_{Comp}^{T_{pl}}$ depends on the consumption schedule, market prices, billing rules, and the availability of renewable energy sources and operation of the energy storage systems. We assume that a minimization of the cost of energy consumed by the company during planning period T_{pl} is completed using one of the developed methods [32–34].

The owners of the EVs, acting individualistically, charge their cars at the place of residence. We suppose that the calculation and minimization of the cost of charging of each individual car i can be made separately. The task of cost minimization for each car can be expressed as follows:

$$C_{EV,i}^{T_{pl}*} = \sum_{t=1}^{T_{pl}} (C_{EV,i}^{t}) \rightarrow min, \forall\ t \in T_{pl}\ ,\ \forall\ i \in N_{EV} \quad (2)$$

where $C_{EV,i}^{t}$ is the cost of the energy consumed by car number i during hour t, and €; $C_{EV,i}^{T_{pl}*}$ is the minimized cost of energy consumed by car i during planning period T_{pl}.

In the case of a coalition (company and N_{EV} cars), there is a desire to minimize the total energy costs. This problem can be expressed as follows:

$$C_{coal}^{T_{pl}*} = \sum_{t=1}^{T_{pl}} (C_{Comp}^{t} + \sum_{i=1}^{N_{EV}} (C_{EV,i}^{t} + C_{resid,i}^{t})) \rightarrow min, \forall\ t \in T_{pl},\ \forall\ i \in N_{EV} \quad (3)$$

where $C_{coal}^{T_{pl}*}$ is the minimized cost of energy consumed by the coalition during planning period $T_{pl.}$, €, and $C_{resid,i}$ is the cost of energy consumed by EV owner number i at their place of residence during hour number t, €.

Note that the formation of a coalition is possible only if the total minimized cost of the coalition is less than the sum of the minimized costs of the potential participants if they act independently from each other, that is, if the following inequality is true:

$$G_{coal} = (C_{comp}^{T_{pl}*} + C_{EV}^{T_{pl}*}) - C_{coal}^{T_{pl}*} > 0 \quad (4)$$

where G_{coal} is the gain of the coalition €.

Costs $C_{coal}^{T_{pl}*}$, $C_{EV,i}^{T_{pl}*}$, and $C_{comp}^{T_{pl}*}$ depend on the battery charge or discharge energy consumed during each hour (decision variables) and its prices (state variables).

The simple forms of Equations (1)–(3) describe very complex tasks, since, in the general case, they are nonlinear, stochastic, multistage expressions and contain a large number of decision and state variables [10,22,35,36]. Indeed, Equation (3) can be presented in the following form:

$$C_{coal}^{T_{pl}*} = F(P_{pr}^{t},\ W^{t},\ W_{ch}^{t},\ W_{disch}^{t},\ W_{mov}^{t}) \quad (5)$$

where F is the costs minimization procedure; P_{pr}^{t}, W^{t}, W_{ch}^{t}, W_{disch}^{t}, and W_{mov}^{t} denote multidimensional processes of change in time; P_{pr}^{t} stands for the energy prices; W^{t} is the amount of electricity consumed by the company and by the residence of each EV (excluding the energy used by EV batteries); W_{ch}^{t} and W_{disch}^{t} stand for the energy amount of charge and discharge of the batteries of each EV; and W_{mov}^{t} is the energy consumption for the movement of each EV. Samples of W_{ch}^{t}, W_{disch}^{t} should be considered as decision variables. Note that the number of decision variables can be quite significant.

Minimization procedures Equations (1)–(3), and (5) must be implemented taking into account many technical and legislative limitations [35,36]. The fulfilment of these limitations, in particular, are to ensure movement along a given route. Usually, the synthesis and application of procedure F is based on the modeling of the process of charging and discharging the car batteries (CDB) [21,37] and taking into account the cost of energy consumption. The CDB models are constructed by using the technical parameters of the batteries and chargers.

3.2. Charging and Discharging of Car Batteries (CDB)

A CDB process is usually characterized by the following main parameters:

- The maximum power W_{BESS} (kWh) represents the maximum energy that the batteries can charge or discharge;
- Charge and discharge efficiency η_{ch} (%) or η_{disch}, respectively, represents the conversion losses during charge or discharge;
- Charge and discharge capacity $W_{ch,h}$ (kWh/h) or $W_{disch,h}$, respectively, signify energy that can be transferred per unit of charge or discharge time;
- Storage efficiency η_{st} (%) describes the time-based losses in the battery energy storage system;
- The estimated number of battery charge cycles, n_{cycle};
- The state of charge (SOC) S_i (%) at any time i characterizes the degree of filling of the battery.

In the problem under consideration, there are two decision variables, the energy charged W_{ch} and the energy discharged W_{disch} at time t, which are non-negative by convention. They are subjected to the following constraints:

$$\begin{cases} W^t_{resid} + W^t_{\text{ch}}/\eta_{ch} \le P_{max,PR} \cdot \tau, \ \forall\, t \in T_{pl} \\ 0 \le W^t_{\text{ch}} \ \le \ P_{ch,\ PR} \cdot \tau, \ \forall\, t \in T_{pl} \end{cases} \tag{6}$$

where W^t_{resid} represents the energy consumption by the EV owners at their place of residence during hour t; kWh; $P_{max,PR}$ is the permissible maximum load of the charging station of the EV owner's place of residence, kW; τ is the time step (τ = 1 h); and $P_{ch,\ PR}$ is the power of the place of residence charging station, kW.

Discharging consumption of electricity is carried out taking into account the following constraints:

$$\begin{cases} W^t_{Comp} - \sum\limits_{i=1}^{N_{EV}} W^t_{disch,i} \cdot \eta_{disch} \ge 0, \ \forall\, t \in T_{pl} \\ 0 \ \le W^t_{disch} \ \le \ P_{ch,\ PW} \cdot \tau, \ \forall\, t \in T_{pl} \end{cases} \tag{7}$$

where W^t_{Comp} is the energy consumption of the company during hour t, kWh and $P_{disch,\ PW}$ is the power of the Company's discharging station, kW.

The state of charge (SOC) [38,39] of batteries S^t can be estimated as follows:

$$S^t = S^{t-1} + W^{t-1}_{\text{ch}} - W^{t-1}_{disch,i} - w^{t-1}_{mov} \cdot \frac{L_{EV}}{2} \tag{8}$$

where L_{EV} is the distance between PR and PW, km and w_{mov} is the specific energy consumption for movement, kWh/km. We assume that the distance L_{EV} is given and known for each EV. The SOC must be within its physical limits as described in the following constraint:

$$\begin{cases} S_{min} < S^t < S_{max} \\ S_f \ge S_{min} + w_{mov} \cdot L_{EV} \\ S_b = S_{min} + w_{mov} \cdot \frac{L_{EV}}{2} \end{cases} \tag{9}$$

where S_f, S_b is the SOC of batteries before moving from the place of residence and from the company, respectively.

3.3. The Cost of Energy Consumption

Samples of P^t_{pr} should be calculated according to the rules of billing considering market prices (state variables), as well as additional taxes and fees that take into account the interests of electric networks and the state. Energy pricing rules are drafted by government agencies and traders. There is a wide variety of account generation rules [32,40,41]. Consumers have the right to choose the most appropriate rules from the set available in each country. The problem of optimizing the scheduling of the charge/discharge of batteries makes sense only if dynamic billing systems are used that take into account hourly changes in energy consumption and its price. Such a system usually consists of three components. The first is proportional to the energy market price at a given hour. The second component is proportional to the energy consumed (without taking into account the market price during the period of consumption). This component includes the sum of additional payments $P_{r\ add}$ such as the trade commission, the electricity distribution fee, an, the mandatory procurement component. The third component is a fixed one, which depends on the capacity value (a capacity-based connection fee to the distribution system operator; the mandatory procurement component for the connection) [41].

The billing rule, taking into account the presence of the named components, can be written down in the following form:

$$C_i^t = k_{m,i} \cdot P_{r\ mark}^t \cdot W_i^t + k_{f,i} \cdot P_{r\ add}^t \cdot W_i^t + P_{fix,i} \tag{10}$$

where C_i^t is the total costs of the i-th end user for the electricity bill at hour t, €; W_i^t is the consumed energy of the i-th end user at hour t, kWh; $P_{r\ mark}^t$ is the electricity market price at hour t, €/kWh; $P_{r\ add}^t$ represents additional variable components of the billing system without the electricity market price at hour t, €/kWh; $k_{m,i}$ and $k_{f,i}$ are proportionality coefficients; and $P_{fix,i}$ is the fixed component of the electricity bill for the i-th end user, €/kW(A)/hour.

The freedom to choose $k_{m,i}$, $k_{f,i}$ and $P_{fix,i}$ is limited by government decisions. Coefficients can be selected by traders, acting within the framework established by the government, and by the consumers choosing the most profitable trader.

It is important to note that the task to be solved requires a description of the system for the entire planning period, which makes it necessary to forecast the parameters of the influencing processes. The forecasting procedure is part of the general procedure for controlling the process in question. The complexity of the forecast depends on the length of the planning period. The uncertainty of the forecast and the number of decision variables increases with an increase in the planning period, which causes additional complications, in particular, when choosing and implementing procedure F. Fortunately, methods presented in scientific publications can be used when predicting processes, selecting and implementing the F procedure, the complexity of which can be reduced by decomposing the planning horizon into a set of smaller subhorizons [42]. If one uses a planning period of one day, the need to predict prices disappears, because, according to the rules, tomorrow's prices become known at a fixed hour [31] of the current day.

Minimization of costs in accordance with Equation (2) while fulfilling inequality Equation (4) and all the technical constraints leads to a solution that guarantees the lowest costs for the coalition. However, the expenses of some members of the coalition can increase. It is necessary to redistribute profits so that there are no victims of the merger. Redistribution of profits is required. Shapley distribution can be used for this.

3.4. The Shapley Approach

If a decision is made to form a coalition and minimize its costs, an additional problem arises regarding the distribution of its winnings between the players. For this, we can use a solution concept introduced by Lloyd Shapley (Nobel Prize in 2012). According to the game theory, the ShV [42,43] describes one approach for fairly distributing the benefits obtained by forming a coalition.

According to the ShV, the amount that player m gets in a given coalitional game (R,N) can be described in the following form:

$$\varphi_m(R) = \sum_{m \notin S \subseteq N} \frac{|S|!(N-1-|S|)!}{N!} \cdot (R(S \cup \{m\}) - R(S)) = \sum_{m \notin S \subseteq N} k_S \cdot (R(S \cup \{m\}) - R(S)) \tag{11}$$

where $N = \{1, \ldots, n\}$is the set of all players; n is the total number of players; $R(S \cup \{m\})$ stands for the gains of coalition S with the participation of the m-th actor; $R(S)$ is the sum of the players' gains, if the coalition is formed without the participation of the m-th player; $|S|$ is the size of set S, the sum includes all subsets S of set N that do not include the m-th player; and k_S is the distribution coefficient of coalition S with the participation of the *m-th* player. To calculate the winnings of players and coalitions (R ($S \cup \{m\}$), R (S)), using Equation (11), it is necessary to solve the optimization problem in the form of Equations (1)–(3). The minimization has to be done for all possible coalitions and player combinations.

It is worth noting that with the increase in the number of players, the number of possible combinations of the coalition is growing exponentially. However, this difficulty can be circumvented by uniting the participants in groups and by excluding impossible coalitions from consideration.

As a result of the distribution of extra winnings, each player receives a share of the total profit, which compensates for additional expenses and takes into account the contribution of each participant to the creation of additional benefits [42].

A simplified diagram of charge/discharge scheduling (including the ShV distribution process) is presented in Figure 2.

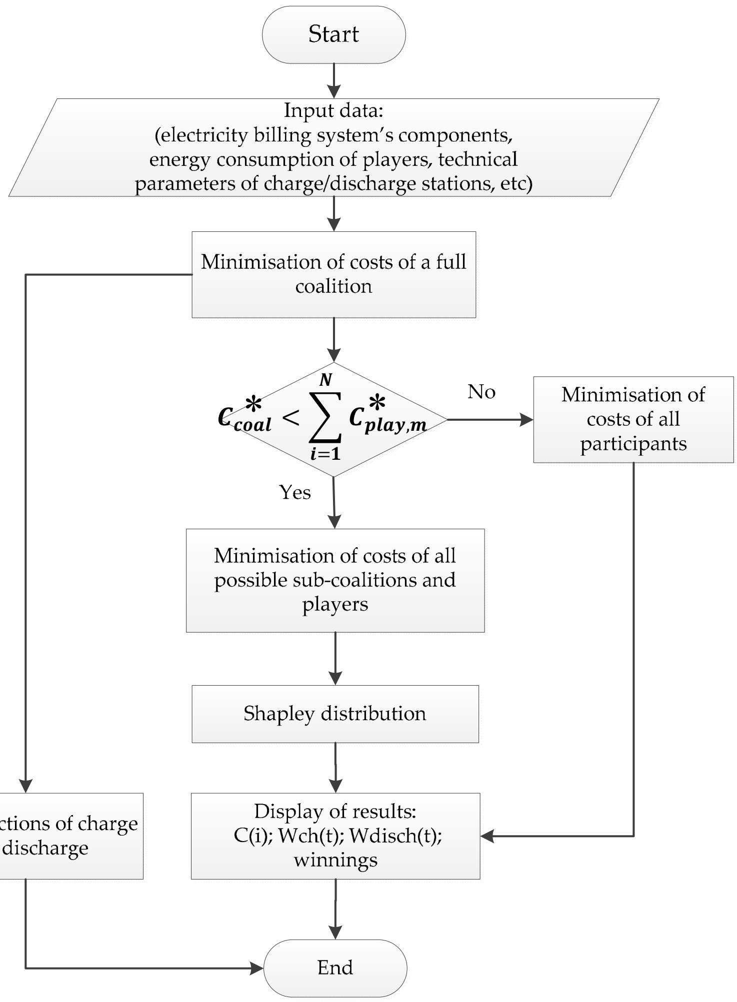

Figure 2. A simplified diagram of charging/discharging scheduling (where $C_{play,m}$ is the minimized cost of energy consumed by each m-th player, separately).

4. Case Study

4.1. Input Data and Assumptions

The following conditions and assumptions were taken into account in the simulation:

- A one-day-long planning period T_{pl} is used for the optimization of the charge/discharge of EV batteries;
- We consider the possibility of forming a coalition of four members, (1) a company with a discharge station (company) and (2) three groups of electrical vehicles (GEV1, GEV2, and GEV3), each of which consists of 10 vehicles with the same technical characteristics. The grouping was carried out on the basis of the distance between the PR and the PW. The average length from PR to PW was assumed to be 5 km for GEV1, 10 km for GEV2 and 15 km for GEV3;
- We assumed that the energy consumption of all participants W_m^t was predetermined and cannot be changed;
- It is assumed that coalitions can be created only with the participation of the Company.
- The number of charge/discharge cycles per day is limited and equal to one;
- The cars are located at the company station from 8:00 till 17:00 and at the place of residence from 22:00 till 7:00;
- A residential station can be used only for charging;
- The company's station can provide discharging of batteries. We assumed that the company's parking lot was used only on regular working weekdays. As a result, there were 248 working days in the year in the region under consideration. The discharge energy was used only for the needs of the company;
- The distribution fee of the energy consumption of the company is divided into three zones, the day zone (from 7:00 to 8:00; from 10:00 to 17:00, and from 20:00 to 23:00), the maximum hour's zone (from 8:00 to 10:00 and from 17:00 to 20:00), and the night zone (from 23:00 to 7:00). In the calculations, we did not take into account the night zone, because of the fact that the EVs are discharged only from 8:00 till 17:00;
- The $P_{r\ add,resid}$ and $P_{r\ add,\ Comp}$ components included the sum of additional payments such as the trade commission, the electricity distribution fee, and the mandatory procurement component for the consumed energy;
- Because of the short lapse of time between the charge and the discharge, we assumed that the capacity losses and the standby losses within a single cycle were equal to zero. The energy storage capacity of the EV batteries was assumed to be 50 kWh. The state of charge (SOC) of the batteries was limited to a range from 20% to 100% of the maximum. The energy consumption per kilometer was assumed to be equal to 0.3 kWh/km;
- The discharging power of the company was 20 kW for one EV;
- We assumed that the SOC of all EVs at midnight was equal to 20%;
- The simulation was performed in MATLAB.

The main economic and technical assumptions are summarized in Table 1.

Table 1. The key assumptions.

Name of the Parameter; Measuring Unit	Value
Sum of additional variable components for the EV owner at the place of residence ($P_{r\ add,\ resid}$), €/kWh [44,45]	0.0767
Fixed component of electricity bill for the EV owner at the place of residence ($P_{fix,resid}$), €/annually [44,45]	168.04
Sum of additional variable components for the company ($P_{r\ add,\ Comp}$), €/kWh [44,45]: - day zone - maximum hours zone	0.0594 0.0754
Fixed component of the electricity bill for the company ($P_{fix,Comp}$), €/A/annually [44,45]	22.67
Energy storage capacity of the EV batteries, kWh	50
Energy consumption per kilometer (w_{mov}), kWh/km	0.3
Number of EVs (N_{EV})	30
Charging efficiency (η_{ch})	0.94
Discharging efficiency (η_{disch})	0.94
Discharging power of the company, kW/EV	20
Rated maximum allowable current of the company, A	1200
Rated maximum allowable current of the residence, A	16
Number of phases at the residence	3

4.2. Calculation of the Costs of Energy Consumed

The energy consumption costs used in the objective functions Equations (1)–(3) can be calculated using Equation (10). We assume that the battery charging schedule does not affect the size of the fixed component and the cost of energy used for the needs of other consumers (excluding batteries). In this case, the total variable price for consumed energy at the PR (for the EV owner) and the PW (for the industrial or commercial consumer) can be calculated in the following form accordingly:

$$\begin{aligned} P^t_{resid,i} &= k_{m,i} \cdot P^t_{r\ mark} + k_{f,i} \cdot P^t_{r\ add,resid,i},\ \forall\ i \in N_{EV},\ \forall\ t \in T_{pl} \\ P^t_{Comp} &= k_m \cdot P^t_{r\ mark} + k_f \cdot P^t_{r\ add,Comp},\ \forall\ t \in T_{pl} \end{aligned} \tag{12}$$

In the case of using the energy stored by the company, the fee to the trader is reduced. This decrease can be estimated as follows:

$$C^t_{Comp} = -\sum_{i=1}^{N_{EV}} W^t_{disch,i} \cdot P^t_{Comp},\ \forall\ t \in T_{pl} \tag{13}$$

Note that in general:

$$P_{r\ add,\ Comp} \neq P_{r\ add,resid} \tag{14}$$

Coefficients k_m and k_f can be selected in the general case, and therefore can be considered as decision variables. To avoid the need to solve the nonlinear problem, we consider the named coefficients as hidden variables [46], the values of which can be found by enumerating their possible values. In the examples below, we present two possible sets of hidden variables.

4.3. Cost Minimization Procedure

Given the assumptions made, the task of minimizing the coalition costs can be written in the following form:

$$C_{coal}^{T_{pl}} = \sum_{T_{ch}=0}^{T_{ch}=7}\sum_{i=1}^{N_{EV}}\left(W_{resid,i}^{t_{ch}} + W_{ch,i}^{t_{ch}}\right)\cdot P_{resid,i}^{t_{ch}} + \sum_{t_{disch}=8}^{T_{disch}=17}\left(W_{Comp}^{t_{disch}} - \sum_{i=1}^{N_{EV}} W_{disch,i}^{t_{disch}}\right)\cdot P_{Comp}^{t_{disch}},\ \forall\, t_{ch}, t_{disch} \in T_{pl} \quad (15)$$

where t_{ch} and t_{disch} represent the start time of EV charging and discharging, respectively; T_{ch} and T_{disch} stand for the end time of EV charging and discharging, respectively.

The solution of Equation (15) should be carried out taking into account the constraints Equations (6) to (9), (14), as well as additional assumptions mentioned in Section 4.1. Despite the need for multiple use of the minimization procedure (see Figure 2), the possibility of using linear programming allows us to solve the problem of distributing additional profit for an acceptable time.

4.4. Example 1

The data displayed in Figures 3 and 4, regarding one randomly selected day of 2018 (6 January 2018), are used in the example below.

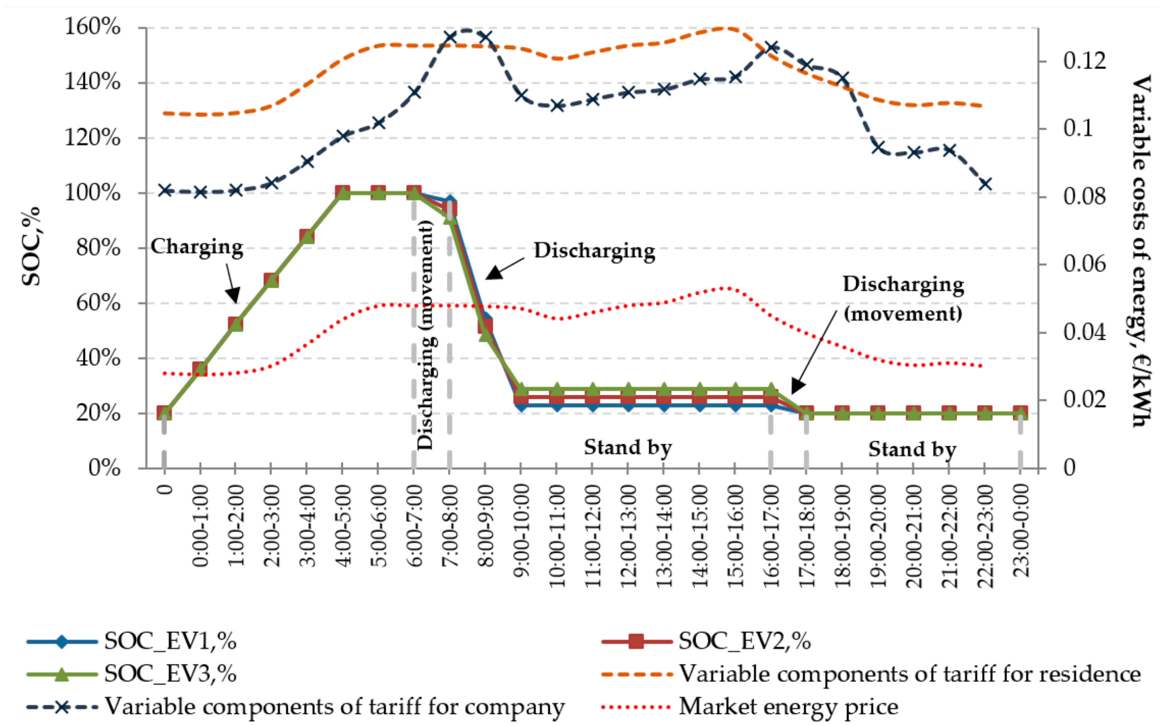

Figure 3. EV's charging/ discharging profile (6 January 2018), applying the existing billing system.

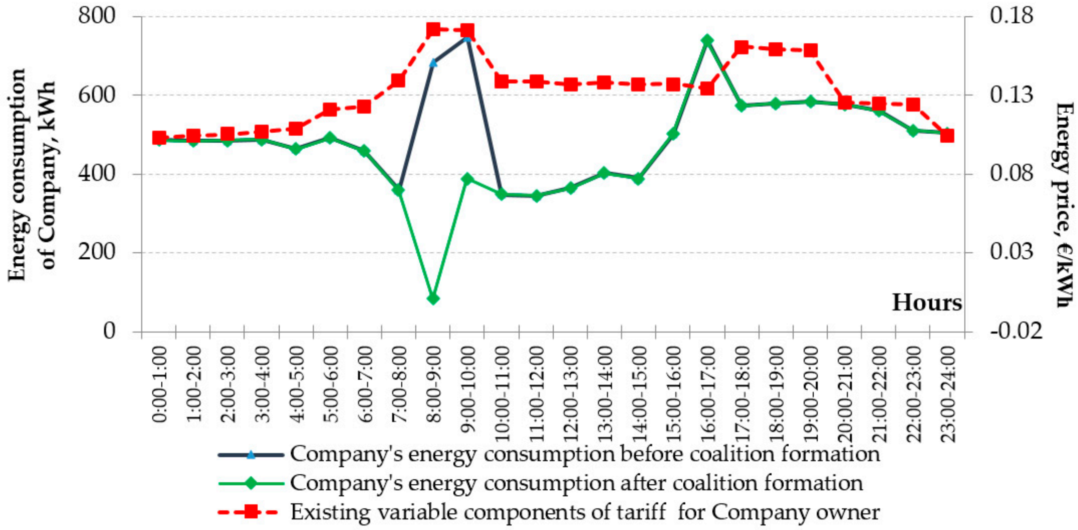

Figure 4. The company's energy consumption and its price, for one day (6 January 2018), applying the existing billing system.

The variability of energy prices over time and depending on the place of connection of the consumer makes it possible to formulate the optimization problem. The optimized GEV1's, GEV2's, and GEV3's car charge/ discharge schedule is given in Figure 3. At night, all the cars charge their batteries and give most of the energy to the company during the morning peak prices.

After receiving energy from the EV owners, it has become possible to smooth the peak loads. The effects are shown on Figure 4.

As a result, the consumption of the energy received from the network during the hours of the morning maximum price is significantly reduced (Figure 4).

The results of calculating the costs and winnings of the players and the distribution of the coalition winnings are presented in Table 2.

Table 2. Charge/discharge expenses of the coalition participants (players), applying the existing billing system.

Situations	Company Expenses, €	GEV1 Expenses, €	GEV2 Expenses, €	GEV3 Expenses, €
Expenses without coalition	0.00	3.30	6.60	10.00
Expenses before the Shapley distribution	−121.90	42.5 (41.90) [1]	42.5 (38.59) [1]	42.5 (35.26) [1]
Expenses after the Shapley distribution	−3.08	2.16	5.58	9.10
Winnings after the Shapley distribution	3.08	1.14	1.02	0.9

[1] The expenses of energy reserved for the transfer to the company.

The GEV cars charge batteries at night at a low price. In the absence of a coalition, the batteries are charged with the energy necessary to move along a given route. In the case of a coalition, the batteries are charged to their full capacity. However, at the same time, the owners of EVs suffer losses because they charge more energy than they consume on the road. This energy is used by the company, which avoids the costs in the volume of 121.90 € (Table 2), sufficient to compensate for the loss of the GEV owners (41.9 €, 38.59 €, and 35.26 €) and receive an additional profit. The travel costs for the automobiles fall by an average of about 20%. Regrettably, the additional profit, in this example, is modest. This is easily explained by the existing consumer billing rules. According to these rules, the market price of electricity determines only a smaller part of the final account (see Figure 3). The greater part of the bill consists of components that are formed only depending on the amount of energy consumed, regardless of its price. As a result, consumers are poorly motivated to adapt the electricity consumption to the market prices. The considered example confirms the above.

4.5. Example 2

In the new example, we introduce changes to the rules for billing electricity consumers. We assume that the bill contains only a component proportional to the price of the electricity market. To account for network costs, traders, and taxes/levies, coefficients k_m = 2.5 and k_f = 0 for EV and k_m = 2.25 and k_f = 0 for the company are used. The choice of the values of these coefficients was made so that the rule changes did not lead to a decrease in the expenses in favor of the network and taxes. The data shown in Figures 5 and 6, similar to Example 1, correspond to the same day (06 January 2018) and use the same EV technical parameters and assumptions.

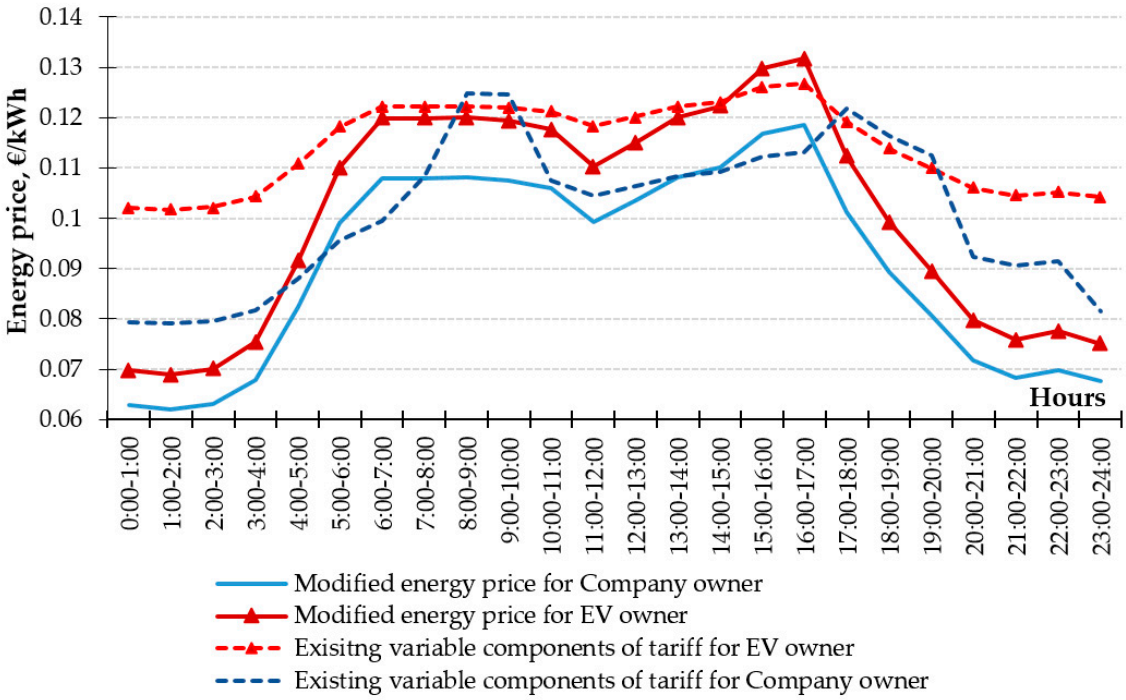

Figure 5. Consumers' energy prices, for one day (6 January 2018).

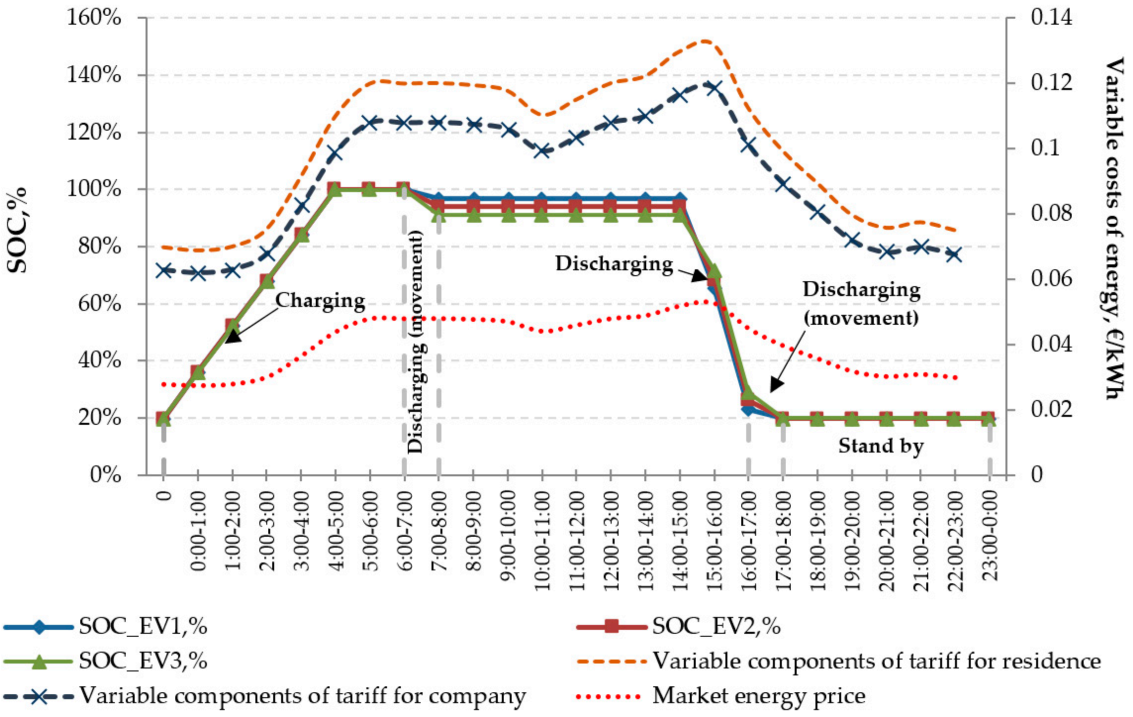

Figure 6. EV's charging/ discharging profile (6 January 2018), applying the new billing system.

Changes in the rules for creating an account led to a reduction in the prices at night (Figure 5), as a result of which the cost of battery charge was significantly reduced. At the same time, the prices rose during the peak hours. The changes in the prices have caused significant changes in the optimal battery discharge schedule (let us compare Figures 5–7).

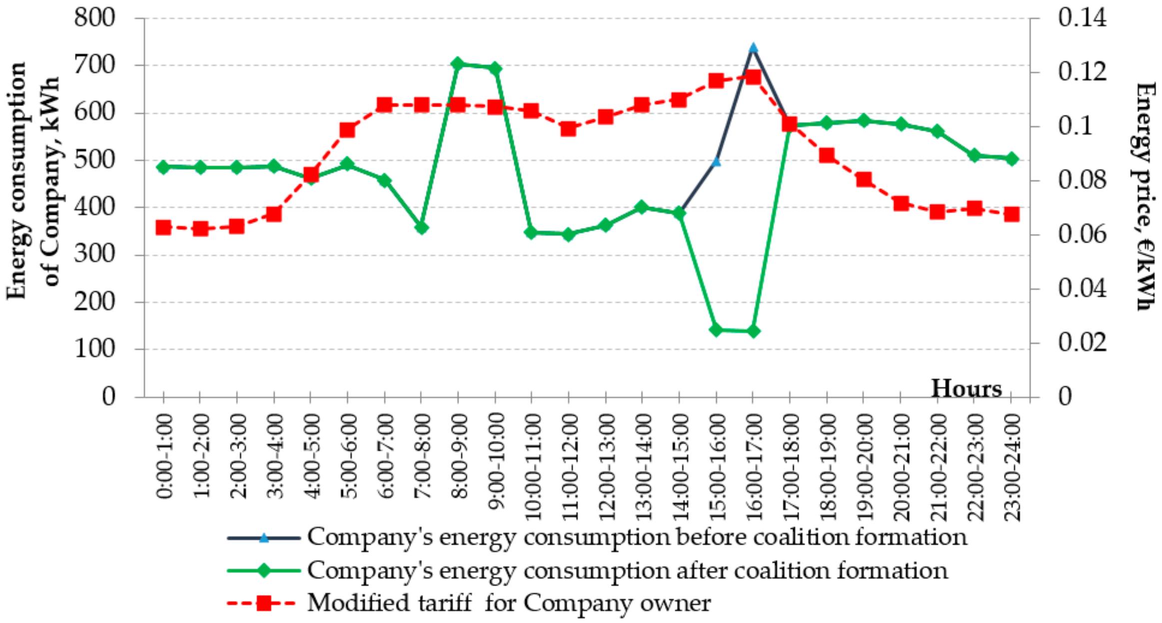

Figure 7. Energy consumption of the company, for one day (6 January 2018), applying the new billing system.

The batteries are discharged during the hours of maximum market prices.

The results of calculating the expenses and winnings of the players and the distribution of coalition winnings are presented in Table 3.

Table 3. Charge/discharge expenses of coalition participants (players), applying the new billing system.

Situations	Company Expenses, €	GEV1 Expenses, €	GEV2 Expenses, €	GEV3 Expenses, €
Expenses without coalition	0	2.2	4.4	6.61
Expenses before the Shapley distribution	−112.89	31.8 (29.6) [1]	31.8 (27.4) [1]	31.8 (25.19) [1]
Expenses after the Shapley distribution	−15.28	−3.25	−0.69	2.06
Winnings after the Shapley distribution	15.28	5.45	5.09	4.55

[1] The expenses of energy reserved for the transfer to the company.

The energy charged by the GEV is used by the company, which avoids costs in the volume of 112.89 € (Table 3), sufficient to compensate for the loss of the GEV owners (29.6 €, 27.4 €, and 25.19 €) and receive an additional profit. The distribution of the additional profit dramatically changes the picture of the costs of the participants. The travel cost amounts for GEV1 and GEV2 reverse. Giving batteries for the needs of the company allows GEV1 and GEV2 not only to fully compensate for travel expenses, but also to make a profit.

4.6. Example 3

A third example is provided to assess the long-term benefits of forming the coalition in question. The length of the planning period is assumed to be one year (Figure 8) and 2018 Nord Pool prices [47] are used in the calculations. The task of optimizing the battery charge is solved for each working day, and the annual costs are determined by summing up all the daily expenses.

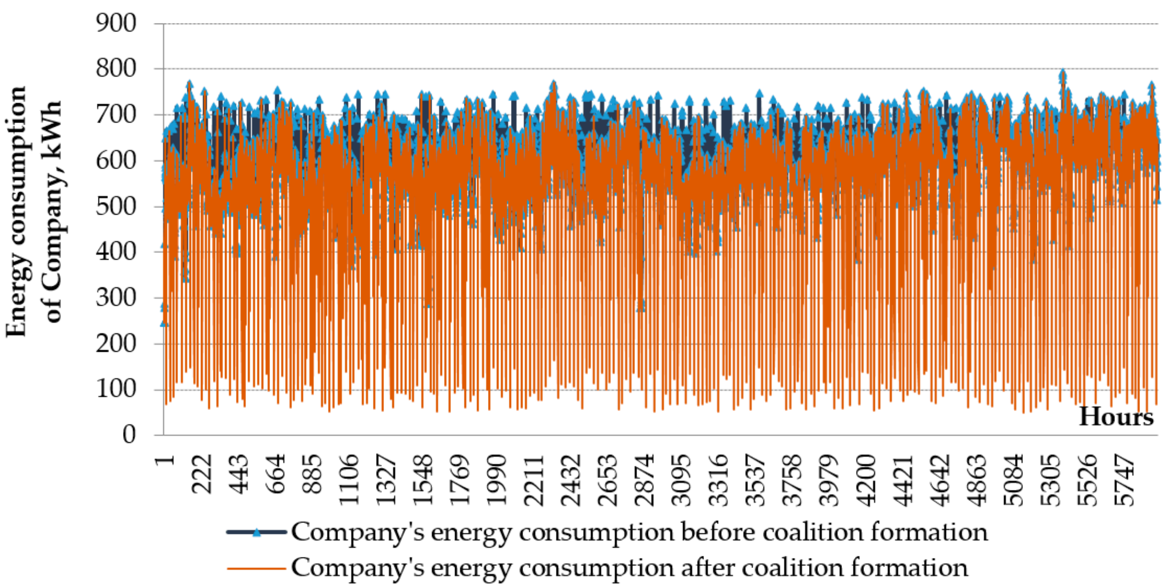

Figure 8. Annual energy consumption of the company, applying the new billing system.

The results of calculating the annual expenses and winnings of the players and the distribution of the coalition winnings are presented in Table 4.

Table 4. Annual charge/discharge expenses of the coalition participants (players), applying the new billing system.

Situations	Company Expenses, €	GEV1 Expenses, €	GEV2 Expenses, €	GEV3 Expenses, €
Expenses without coalition	0.00	736.41	1472.82	2217.01
Expenses before the Shapley distribution	−35,899.16	10,878.21 (11,614.62) [1]	10,141.80 (11,614.62) [1]	9397.61 (11,614.62) [1]
Expenses after the Shapley distribution	−2740.23	−320.41	560.71	1445.72
Winnings after the Shapley distribution	2740.23	1056.82	912.11	771.29

[1] The expenses of energy reserved for the transfer to the company.

The energy charged by the GEVs is used by the company, which avoids costs in the volume of 35,899.16 € (Table 4), sufficient to compensate for the loss of the GEV owners (10,878.21 €, 10,141.80 €, and 9397.61 €) and receive an additional profit. The travel costs of GEV1 reverse. Giving batteries for the needs of the company allows GEV1 not only to fully compensate for travel expenses, but also to make a profit. The costs of groups GEV2 and GEV3 decrease approximately three and two times, respectively. It is important to note that as a result of fluctuations in the market prices, not all the days meet the conditions for forming a coalition. In this example, based on the 2018 prices, out of 248 working days for the formation of a coalition, the following were favorable: for GEV1, 200 days; for GEV2, 198 days; and for GEV3, 194 days.

5. Discussion

Creating coalitions that include employers and employees who own electric vehicles can be beneficial to all participants. The profitability of the coalition depends heavily on price fluctuations and billing rules, which vary from country to country. The business idea discussed in the examples is not the only one. There may be conditions when it is profitable to charge cars at a company's parking lot and discharge them at a place of residence; a distribution grid can participate in the coalition. One can get additional benefits by participating in intraday, balancing (primary and secondary frequency control and voltage regulation), or capacity markets [48].

The above-mentioned possibilities form the basis of further research aimed at accelerating the electrification of transport.

Let us note that the final decision on the division of the coalition profits should be taken by the coalition members during the negotiations, as the Shapley distribution is not a legislative act that forces members to cooperate in accordance with the cooperative game theory. The described methodology and results only facilitate the correct decision making.

6. Conclusions

An EV can be used to create flexible, time-controlled electrical network loads. At the same time, contrasting other technologies that consume energy, the EV is able to change the consumption schedule in time and also in space, choosing the place of charging/discharging the batteries. This property can be useful for all participants in the energy supply process.

Most of the time, electric cars are parked at two places, at the place of residence and at the company of the employer. This fact allows planning the charging of batteries, taking into account the interests of the employer and the owner of the EV. In assessing the profitability of projects for the construction and control of charging stations, one should consider the possibility of creating a coalition of station owners and EVs. Equitable distribution of coalition winnings can contribute to the spread of EVs, reduce emissions into the atmosphere, and improve the efficiency of energy supply. The Shapley approach provides a methodological basis for implementing a rational distribution of winnings derived from concerted actions of coalition members.

Author Contributions: The main idea was proposed by all the authors. M.Z.-B. and A.S. contributed the methodology and data curation; L.P. and R.P. wrote the model software and performed the calculations for the study; All authors have read and agreed to the published version of the manuscript.

Funding: This work was funded by the European Regional Development Fund within the Activity 1.1.1.2 "Postdoctoral Research Aid" of the Specific Aid Objective 1.1.1 "To increase the research and innovative capacity of scientific institutions of Latvia and the ability to attract external financing, investing in human resources and infrastructure" of the Operational Programme "Growth and Employment" (no. 1.1.1.2/VIAA/2/18/317 and no. 1.1.1.2/VIAA/1/16/021).This work was founded by the Latvian Council of Science, project Management and Operation of an Intelligent Power System (I-POWER) (no. lzp-2018/1-0066).

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

Nomenclature

N_{EV}	Total number of users of the parking lots (total number of EVs)
T_{pl}	Number of sampling steps Δt (e.g., one hour) in the planning period of optimization
C^t_{Comp}	Cost of energy consumed by the company during hour number t (€)
$C^{T_{pl}}_{comp}$	Minimized cost of energy consumed by the company during planning period T_{pl}
i	Number of each individual EV
$C^t_{EV,i}$	Cost of energy consumed by car number i during hour number t (€)
$C^{T_{pl}}_{EV,i}$	Minimized cost of energy consumed by car i during planning period T_{pl} (€)
$C^{T_{pl}}_{coal}$	Minimized cost of energy consumed by coalition during planning period T_{pl} (€)
$C_{play,m}$	Minimized cost of energy consumed by each m-th player, separately (€)
G_{coal}	Gain of coalition (€)
$C^t_{resid,i}$	Cost of energy consumed by EV owner number i at residence during hour number t (€)
F	Costs minimization procedure
P^t_{pr}	Energy prices at hour t (€/kWh)
W^t	Amount of electricity consumed by the company and by the residence of each EV (excluding energy used by EV batteries) (kWh)
W^t_{ch}, W^t_{disch}	Energy amount of charge and discharge of batteries of EV (kWh)
W^t_{mov}	Energy consumption for the movement of each EV (kWh)
$W_{ch,h}$, $W_{disch,h}$	Charge and discharge capacity, correspondingly signifying energy that can be transferred per unit of charge or discharge time (kWh/h)
η_{st}	Storage efficiency
S_i	State of charge of car i
η_{ch}	Charging efficiency coefficient
W^t_{resid}	Energy consumption by EV owner at residence during hour t (kWh)
$P_{max,PR}$	Permissible maximum load of EV owner's residence (kW)
τ	Time step (τ = 1 h)
$P_{ch,\ PR}$	Capacity of residence charging station (kW)
η_{disch}	Discharging efficiency coefficient
W^t_{Comp}	Energy consumption of the company during hour t (kWh)
$P_{disch,\ PW}$	Capacity of the company's discharging station (kW)
L_{EV}	Distance between the PR and PW (km)
	Specific energy consumption for movement (kWh/km)
S_f, S_b	SOC of batteries before moving from the place of residence and from the company, respectively
C^t_i	Total costs of i-th end user for the electricity bill at hour t (€)
W^t_i	Consumed energy of i-th end user at hour t (kWh)
$P^t_{r\ mark}$	Electricity market price at hour t (€/kWh)
$P^t_{r\ add}$	Additional variable components of the billing system without the electricity market price at hour t, (€/kWh)
$k_{m,i}$, $k_{f,i}$	Proportionality coefficients

$P_{fix,i}$	Fixed component of electricity bill for the i-th end user (€/kW(A)/hourly(annually))
$N = \{1, \ldots, n\}$	Set of all players
n	Total number of players
m	Number of each individual player
$R(S \cup \{m\})$	Gains of coalition S with the participation of the m-th actor (€)
$R(S)$	Sum of the players' gains, if the coalition is formed without the participation of the m-th player (€)
$\|S\|$	Size of set S, the sum includes all subsets S of set N that do not include the m-th player
$k_{S,m}$	Distribution coefficient of coalition S with the participation of the m-th player
t_{ch}, t_{disch}	Start time of EV charging and discharging, respectively
T_{ch}, T_{disch}	End time of EV charging and discharging, respectively
n_{cycle}	Number of battery charge cycles
Acronyms	
EV	Electrical vehicle
PHEV	Plug-in hybrid electrical vehicle
ShV	Shapley value
PR	Place of residence
PW	Place of work
CDB	Charging and discharging of car batteries
GEV	Group of electrical vehicles
SOC	State of charge

References

1. IRENA. Renewable Energy Statistics 2019. The International Renewable Energy Agency, Abu Dhabi. Available online: https://www.irena.org/publications/2019/Jul/Renewable-energy-statistics-2019 (accessed on 10 October 2019).
2. European Commission Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009 on the Promotion of the Use of Energy from Renewable Sources and Amending and Subsequently Repealing Directives 2001/77/EC and 2003/30/EC (2009). Available online: https://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2009:140:0016:0062:en:PDF (accessed on 20 July 2019).
3. Renewable Energy Regulation. Available online: http://data.consilium.xn--opa-j50a.eu/doc/document/PE-48-2018-INIT/en/pdfhttp://data.consilium.€opa.eu/doc/document/PE-48-2018-INIT/en/pdf (accessed on 28 July 2019).
4. Energy 2020. A Strategy for Competitive, Sustainable and Secure Energy. Available online: https://ec.europa.eu/energy/en/topics/energy-strategy-and-energy-union/2020-energy-strategy (accessed on 17 July 2019).
5. Zima-Bočkarjova, M.; Sauhats, A.; Petrichenko, L.; Pertichenko, R. Shapley-Value-Based Charging and Discharging Scheduling for Electric Vehicles in a Parking Station. In Proceedings of the 2019 IEEE 60th International Scientific Conference on Power and Electrical Engineering of Riga Technical University (RTUCON), Riga, Latvia, 7–9 October 2019; pp. 1–6. [CrossRef]
6. European Commission. Energy Efficiency Directive—European Commission. Available online: https://ec.europa.eu/energy/en/topics/energy-efficiency/energy-efficiency-directive (accessed on 5 August 2019).
7. Renewable Energy in Europe—2018. Recent Growth and Knock-on Effects. In *EEA Report No 20/2018*; Publications Office of the European Union: Luxembourg, 2018. [CrossRef]
8. Global EV Outlook 2019. Scaling-up the Transition to Electric Mobility. Available online: https://www.iea.org/reports/global-ev-outlook-2019 (accessed on 20 May 2019).
9. Transport and Environment 2018 Report. Available online: https://www.transportenvironment.org/annual-report-2018/documents/TE-Annual-Report-2018.pdf (accessed on 19 July 2019).
10. Osório, G.J.; Shafie-khah, M.; Coimbra, P.D.L.; Lotfi, M.; Catalão, J.P.S. Distribution System Operation with Electric Vehicle Charging Schedules and Renewable Energy Resources. *Energies* **2018**, *11*, 3117. [CrossRef]
11. Damiano, A.; Marongiu, I.; Porru, M.; Serpi, A. Electric Vehicle Energy Storage Management for Renewable Energy Sources Exploitation. In Proceedings of the 2012 IEEE International Electric Vehicle Conference (IEVC 2012), Greenville, SC, USA, 4–8 March 2012; pp. 1–8. [CrossRef]

12. Liu, Y.; Xu, Q.; Zang, H.; Zeng, P.; Xu, X.; Ding, M. Research on the Evaluation Method of Capacity on Electric-Vehicle Energy Storage System. In Proceedings of the 2014 IEEE International Workshop on Intelligent Energy Systems, San Diego, CA, USA, 5–8 October 2014. [CrossRef]
13. Markel, T.; Simpson, A. Plug-In Hybrid Electric Vehicle Energy Storage System Design. In Proceedings of the Advanced Automotive Battery Conference, Baltimore, MD, USA, 17–19 May 2006; National Renewable Energy Laboratory (NREL): Golden, CO, USA, 2006.
14. Paterakis, N.; Erdinc, O.; Pappi, I.N.; Bakirtzis, G.A.; Catalão, J. Coordinated Operation of a Neighborhood of Smart Households Comprising Electric Vehicles, Energy Storage and Distributed Generation. *IEEE Trans. Smart Grid* **2016**, *7*, 2736–2747. [CrossRef]
15. Sundstrom, O.; Binding, C. Optimization Methods to Plan the Charging of Electric Vehicle Fleets. *ACEEE Int. J. Commun.* **2010**, *1*, 45–50.
16. Martínez, I.J.; García-Villalobos, J.; Zamora, I. Energy management of micro renewable energy source and electric vehicles at home level. *J. Mod. Power Syst. Clean Energy* **2017**, *6*, 979–990. [CrossRef]
17. Wang, M.; Zeng, P.; Mu, Y.; Liang, W.; Qi, Y. An Efficient Power Plant Model of Electric Vehicles Considering the Travel Behaviors of EV Users. In Proceedings of the 2014 International Conference on Power System Technology, Chengdu, China, 20–22 October 2014; IEEE: Piscataway Township, NJ, USA. [CrossRef]
18. Bessler, S.; Grønbæk, J. Routing EV Users towards an Optimal Charging Plan. *World Electr. Veh. J.* **2012**, *5*, 688–695. [CrossRef]
19. Mahmoudi, C.; Flah, A.; Sbita, L. An Overview of Electric Vehicle Concept and Power Management Strategies. In Proceedings of the 2014 International Conference on Electrical Sciences and Technologies in Maghreb (CISTEM), Tunis, Tunisia, 3–6 November 2014; pp. 1–8. [CrossRef]
20. Rizopoulos, D.; Esztergár-Kiss, D. A Method for the Optimization of Daily Activity Chains Including Electric Vehicles. *Energies* **2020**, *13*. [CrossRef]
21. Limmer, S. Evaluation of Optimization-Based EV Charging Scheduling with Load Limit in a Realistic Scenario. *Energies* **2019**, *12*, 4730. [CrossRef]
22. Madina, C.; Zamora, I.; Zabala, E. Methodology for assessing electric vehicle charging infrastructure business models. *Energy Policy* **2016**, *89*, 284–293. [CrossRef]
23. Ding, J.; Zhong, W.; Liu, Y.; Xie, S. PHEV Charging and Discharging Cooperation in V2G Networks: A Coalition Game Approach. *IEEE Internet Things J.* **2014**, *1*, 578–589. [CrossRef]
24. Zhang, R.; Cheng, X.; Yang, L. Flexible Energy Management Protocol for Cooperative EV-to-EV Charging. *IEEE Trans. Intell. Transp. Syst.* **2019**, *20*, 172–184. [CrossRef]
25. Zou, F.; Liu, N.; Chen, Q. Multi-Party Energy Management for EV Charging Station Cooperated with PV Systems in Smart Grid. In Proceedings of the 2015 IEEE Innovative Smart Grid Technologies—Asia (ISGT ASIA), Bangkok, Thailand, 4–6 November 2015; pp. 1–6. [CrossRef]
26. Zhigang, W. Research on Profit Distribution Strategy of Electric Vehicles Absorbing Wind Power Based on Cooperative Game. In Proceedings of the 2nd IEEE Conference on Energy Internet and Energy System Integration (EI2), Beijing, China, 20–22 October 2018; pp. 1–6. [CrossRef]
27. Beaude, O.; Lasaulce, S.; Hennebel, M. Charging Games in Networks of Electrical Vehicles. In Proceedings of the 6th International Conference on Network Games, Control and Optimization (NetGCooP), Avignon, France, 28–30 November 2012; pp. 96–103.
28. Shuang, Y.; Min, Y. Study on Cooperative Games in Electric Vehicle Charging Market on Account of Shapley Distribution Model. *Adv. Mater. Res.* **2014**, *986–987*, 556–559. [CrossRef]
29. Perez-Diaz, A.; Gerding, E.; McGroarty, F. Coordination of Electric Vehicle Aggregators: A Coalitional Approach. In Proceedings of the 17th International Conference on Autonomous Agents and Multiagent Systems, Stockholm, Sweden, 10–15 July 2018; International Foundation for Autonomous Agents and Multiagent Systems (IFAAMAS). pp. 676–684.
30. Project "My Electric Avenue". Available online: http://myelectricavenue.info/ (accessed on 3 August 2019).
31. Nord Pool Day-Ahead Market. Available online: https://www.nordpoolgroup.com/the-power-market/Day-ahead-market/ (accessed on 28 September 2019).
32. Petrichenko, L.; Broka, Z.; Sauhats, A.; Bezrukovs, D. Cost-Benefit Analysis of Li-Ion Batteries in a Distribution Network. In Proceedings of the 15th International Conference on the European Energy Market (EEM), Łódź, Poland, 27–29 June 2018; pp. 1–5.

33. Ghassemi, A.; Goudarzi, P.; Mirsarraf, M.R.; Gulliver, T.A. A Stochastic Approach to Energy Cost Minimization in Smart-Grid-Enabled Data Center Network. *J. Comput. Netw. Commun.* **2019**, *2019*, 4390917. [CrossRef]
34. Vanika, S.; Mohammed, H.H.; Syed Mahfuzul, A. Energy cost minimization for net zero energy homes through optimal sizing of battery storage system. *J. Renew. Energy* **2019**, *141*, 278–286. [CrossRef]
35. Powell, W.B.; Meisel, S. Tutorial on Stochastic Optimisation in Energy Part I: Models and Policies. *IEEE Trans. Power Syst.* **2016**, *31*, 1459–1467. [CrossRef]
36. Nguyen, T.A.; Byrne, R.H. Maximizing the Cost-Savings for Time-Of-Use and Net-Metering Customers Using Behind-the-Meter Energy Storage Systems. In Proceedings of the 2017 North American Power Symposium (NAPS), Morgantown, WV, USA, 17–19 September 2017; pp. 1–6. [CrossRef]
37. Abronzini, U.; Attaianese, C.; D'Arpino, M.; Di Monaco, M.; Tomasso, G. Cost Minimization Energy Control Including Battery Aging for Multi-Source EV Charging Station. *Electronics* **2019**, *8*. [CrossRef]
38. Ohue, K.; Utsunomiya, T.; Hatozaki, O.; Yoshimoto, N.; Egashira, M.; Morita, M. Self-discharge behavior of polyacenic semiconductor and graphite negative electrodes for lithium-ion batteries. *J. Power Sources* **2011**, *196*, 3604–3610. [CrossRef]
39. Nunotani, K. Development and Performance Evaluation of Lithium Iron Phosphate Battery with Superior Rapid Charging Performance—Second Report: Evaluation of battery Capacity Loss Characteristics. In Proceedings of the 2011 IEEE Vehicle Power and Propulsion Conference, Chicago, IL, USA, 6–9 September 2011; pp. 1–4.
40. Triki, C.; Violi, A. Dynamic pricing of electricity in retail markets. *4OR* **2009**, *7*, 21–36. [CrossRef]
41. Grave, K.; Breitschopf, B.; Ordonez, J.; Wachsmuth, J.; Boeve, S.; Smith, M.; Schubert, T.; Friedrichsen, N.; Herbst, A.; Eckartz, K.; et al. Final Report: Prices and Costs of EU Energy. 29 April, 2016, Ecofys 2016 by order of: European Commission. Available online: https://www.isi.fraunhofer.de/content/dam/isi/dokumente/ccx/2016/report_ecofys2016.pdf (accessed on 5 January 2020).
42. Shapley, L.S.A. Value for n-Person Games. In *Contributions to the Theory of Games II*; Kuhn, H.W., Tucker, A.W., Eds.; Annals of Mathematical Studies v. 28; Princeton University Press: Princeton, NJ, USA, 1953; pp. 307–317.
43. Chuang, A.S.; Wu, F.; Varaiya, P. A game-theoretic model for generation expansion planning: Problem formulation and numerical comparisons. *IEEE Trans. Power Syst.* **2001**, *16*, 885–891. [CrossRef]
44. AS "Sadales tīkls" Electricity Distribution Differential Tariffs (January 2020). Available online: https://www.sadalestikls.lv/uploads/2020/01/ST_tarifi_2020.pdf (accessed on 1 January 2020).
45. Tariffs of Mandatory Procurement Components. Available online: https://sprk.gov.lv/content/tarifi-1 (accessed on 1 August 2019).
46. Elidan, G.; Lotner, N.; Friedman, N.; Koller, D. *Discovering Hidden Variables: A Structure-Based Approach*; Leen, T.K., Dietterich, T.G., Tresp, V., Eds.; MIT Press: Cambridge, MA, USA, 2001.
47. Nord Pool Electrical Energy Price Statistics. Available online: http://www.nordpoolspot.com/Market-data1/Elspot/Area-Prices/ (accessed on 1 August 2019).
48. Baltic Balancing Market. Available online: https://dashboard-baltic.electricity-balancing.eu/en (accessed on 1 February 2020).