A Catallaxy-based Market Mechanism for Power Balancing

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***Abstract*—In this paper a Catallaxy-based market mechanism is proposed for power balancing algorithms. Here, all market participants are self-organizing and coordinate themselves without any central control. This approach is highly flexible allowing for different types of negotiations on different time scales. For application in power systems we present a two-tier approach, where energy brokers assemble complex load profiles for customers. A distributed control algorithm is presented to match power demand and supply. This example shows the functionality of a free market design.**

***Index Terms*—Catallaxy, resource pricing, power balancing, peer-to-peer**

I. Introduction

The power system evolves from a centralized system with a small number of large generators towards a liberalized open market with an increasing number of small distributed energy resources, in particular renewables. Furthermore, the availability of smart meters coupled with home energy management at the consumers is increasing. Hence, also the control of power consumption with demand side management becomes feasible. In the long term, storage devices like battery banks will allow to buffer electricity in larger amounts efficiently and economically. In summary, the number of controllable appliances increases considerably.

To ensure the stability of power systems with a large number of distributed energy resources (DER), control and balancing algorithms must also be distributed. Furthermore, algorithms have to cope with insufficient information, a large number of variables and appliances under the control of different entities with different objectives. New energy balancing algorithms are frequently studied in the domain of multi-agent systems (see [1] and the references therein) and, to provide incentives to the different stakeholders, market-oriented mechanisms, e.g. double auctions, are applied [2], [3], [4], [5]. To the best of our knowledge the current literature discusses market-mechanisms that are restricted to a single type of auction and central servers to host the market or auction platform. However, when the number of DERs increases and sellers and buyers are interested in different services for different time periods, this approach lacks flexibility and scalability.

One restriction is a fixed time interval for which power is allocated. Often auctions are carried out for every 15 minute time slot. This restriction has the following shortcomings. On the one hand, renewable resources like photovoltaics and wind power are not able to guarantee constant power generation but are fluctuating over time. On the other hand, intelligent loads are interested in allocations for multiple consecutive time slots. Hence, different market participants are interested in the allocation of power on different time scales. This can be realized by a Catallaxy-based market mechanism as proposed in this paper.

In this work we propose a free-market approach for power balancing that is based on Catallaxy. The term *Catallaxy* [6] comes from the economist and Nobel Prize winner Friedrich August von Hayek. The basic concept is about a free market system without any centralized control. Market participants act according their selfish objectives. They bargain with others for the required resources without having global knowledge about every market detail. To reach their selfish goals they look continuously for alternative trading partners. Hence, a spontaneous order evolves towards a functioning market without any central authority or central marketplace. One advantage of the Catallaxy approach is scalability. Although more coordination messages have to be exchanged in a fully distributed system, the messaging load is distributed over all the nodes in the network. Without a central server no single-point-of-failure exists in the system. Furthermore, entities do not have to trust a central authority. This eliminates the risk of monopoly and ensures privacy protection. Another advantage is the flexibility of the Catallaxy approach, because any service can be offered and any two market participants can agree on any type of negotiation.

This paper is structured as follows. In Section II the basic idea of a Catallaxy-based market for power balancing is outlined. It is compared to a centralized market model in Section III. In Section IV we propose a simple distributed algorithm for a bargaining protocol. In examples, we demonstrate that the convergence of the distributed bargaining algorithm to the market equilibrium depends on the number of negotiations with other market actors. Section V concludes the paper and presents directions of future work.

II. Catallaxy-based Market Mechanism

With the liberalization of the energy market and the increasing number of distributed energy resources new market-models based on monetary or virtual prices are developed to realize new power balancing algorithms. Electronic market places are proposed in different research papers (e.g. in [2],

[3], [4], [5] and the references therein). Although the market participants in these models act autonomously depending on their individual goals, some form of centralized coordination is assumed. For example, in [3] one or multiple PowerMatcher run a Walrasian auction and in [5] order books for each commodity are assumed to be hosted in a centralized way. As sketched in Figure 1(a) the architecture is centralized even if market participants act autonomously.

In this work we propose a Catallaxy-based market approach. The main idea of Catallaxy is a free market without a central authority. Market participants are self-organizing and follow their own objectives. As sketched in Figure 1(b) the topology of the distributed market is a meshed network[1]. Furthermore, it is not static but changes over time depending on the users' strategy. These features are identical to peer-to-peer (P2P) networks. P2P networks offer a scalable and resilient ICT architecture. In contrast to client/sever, where resources are offered at dedicated servers, a P2P system is a self-organizing system of equal, autonomous entities (peers) which aims for the shared usage of distributed resources without central control [7]. Examples of the application of the P2P concepts to power systems, in particular to micro grids, are presented in [8], [9].

The Catallaxy approach by Hayek is based on observations on real markets with human interactions. So far, no formal description of the market mechanisms exists. However, electronic market places in different domains are approaching the concept. Eymann et al. outline in [10] a Catallaxy-based market for Grid computing [11]. They identified three main characteristics of the Catallaxy approach: (i) market participants are self-interested entities maximizing their own utility, (ii) each entity has only limited knowledge about the whole system and can not accurately determine the benefit of alternative actions; it makes decisions also when uncertainty is present, (iii) the market is the set of communications between its participants, it is not centralized but distributed and it is changing dynamically because entities look for alternative trading partners.

In this work we apply the Catallaxy-based market model to power systems for balancing demand and supply in a distributed way. We propose a two-tier architecture consisting of a resource layer and a service layer similar to the approach for Grid Computing in [10]. The separation of resources and services enables provisioning of basic services, service reuse, and efficient service composition to create advanced services. Basic services are directly deployed on top of the resource layer, e.g. *supply power of 1000W from 8 a.m. to 8.15 a.m.*. In the service layer basic services can be reused, combined and orchestrated such that users can be provided with more complex services, e.g. *provide power for the household X for 24 hrs*.

This layered approach has several advantages: end-users do not have to cope with buying power on a small time-scale like minutes or hours. Hence, they need not rely on forecasts about future power supply/demand. The complex service is offered to the users by energy brokers that assemble the complex service by a set of basic services.

Energy brokers contract several generators and loads with different supply and demand characteristics to balance their contracted energy allocations. Furthermore, they offer different services to the intelligent loads such that loads are more flexible in the amount and time interval. If a broker has contracts with several households, the stochastic consumption is flattened by multiplexing. The broker buys power from energy providers. All transactions are done bilateral and different forms of negotiation are possible. Since end-users can contact several brokers and brokers negotiate with different power providers, a fully distributed market evolves. In contrast to the centralized market, complete information about all demands and supplies has not to be available at one node. Furthermore, a node with more information and more connections to others for negotiation is likely to achieve better prices. However, disproportionate amounts of information gathering may also come at an additional cost, regulating the information distribution within the market.

The flexibility of the Catallaxy approach ensures a seamless deployment of new control concepts, because different concepts can coexist in parallel. For example, nowadays most small DERs are passive. The owner is free in her decision to apply new control concepts or stick to the old ones. However, with better control concepts she might provide higher-prized services. Similar households may choose a tariff with a fixed price for each kWh. However, a tariff with dynamic prices according to the actual power balance should be cheaper to them.

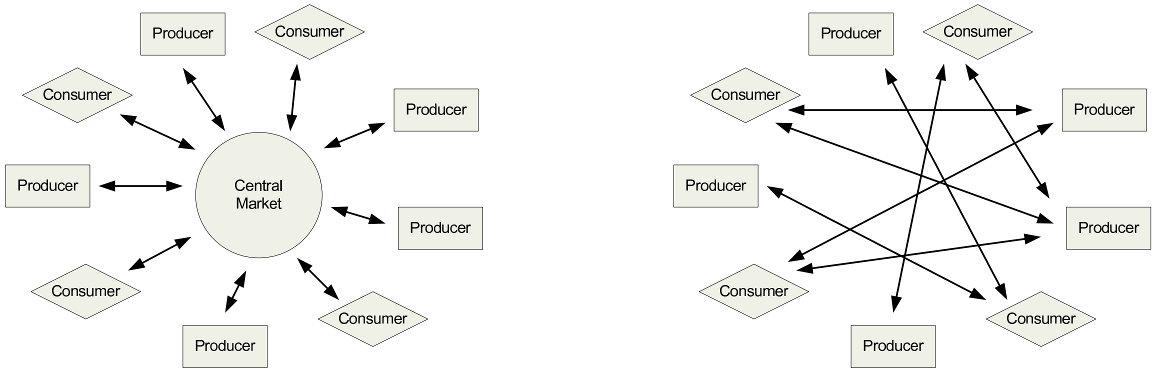
III. Comparison to a central market

This section starts with a description of a simple centralized market platform. It is used for comparison with a Catallaxy-based approach in the following.

In the centralized model energy producer and consumer submit their demand curves to the market platform. The bids are submitted for a specific time interval. For example, by setting the time interval to 15 minutes each day consists of 96 slots for which energy is traded. The market is cleared before the according time slot starts. The exact point of time depends on the implementation of the market.

Like in [12] we use a Walrasian auction to match supply and demand. Here, each energy producer and consumer determines her demand for every possible price. Energy supply of a producer can be expressed as a negative demand. The demand function depends implicitly on the utility gained by the user for a specific amount of the commodity. For example, a simple electronic device needs a specific power level for operation. Hence, the user willing to run this device gains a specific utility when the power level is supplied. Utility is zero for all power levels below this threshold. Furthermore, any additional amount of power has no value for the user when she is only interested in running the device. Hence, the utility function

[1]The topology of the market is a logical network which describes negotiations between its participants. It has not to reflect the topology of the power grid.



(a) centralized

(b) distributed

Fig. 1. Centralized vs. distributed market coordination

for this example is a step function with a step at the power demand of the device.

In mathematical models of markets the discontinuities of step functions introduce integer constraints to the problem. To simplify the mathematical model often sigmoid functions are used instead. Sigmoid functions are continuous and differentiable. Hence, the mathematical problem becomes tractable. Figure 2 presents the results for a small number of producers and consumers for two different points in time. Solid lines represent the demand functions of market participants. Energy producers have negative demand functions. The dashed line represents the aggregation of all demands. When the aggregated demand function is equal zero the market is in equilibrium, where demand and supply are equal. The equilibrium price for the example in Figure 2(a) and in Figure 2(b) is $p_1^* = 78$ and $p_2^* = 107$, respectively.

Figure 2 presents the market outcome for two different points in time. At $t = t_1$ in Figure 2(a) two producers and two consumers participate in the market. At the equilibrium price the energy allocations of both consumers are identical to their maximum demands. To a later point in time, i.e. $t = t_2$, another customer (i.e. $c3$) is present on the market. She has a higher maximum demand and is willing to pay higher prices for it. Hence, at equilibrium of demand and supply the customer $c3$ changes the allocation of power. Only customers $c1$ and $c3$ can be serviced. The allocation of the customer $c2$ drops in Figure 2(b) to zero.

With these market outcomes the following question arises: Does the allocation at t_1 has any value for the customer $c2$ when no power is allocated at t_2? Also in the central market model each participant acts autonomously and is interested in maximizing her own benefit. Hence, it is her own responsibility to define a strategy such that an allocation has a value for her. Different possibilities exist for customer $c2$ to avoid this market outcome. For example, she can submit different demand functions for different points in time. Therefore, she has to compare between risk and benefit of her strategy and their alternatives. Furthermore, she has no knowledge about the strategies of the other market participants but may try to forecast their behavior.

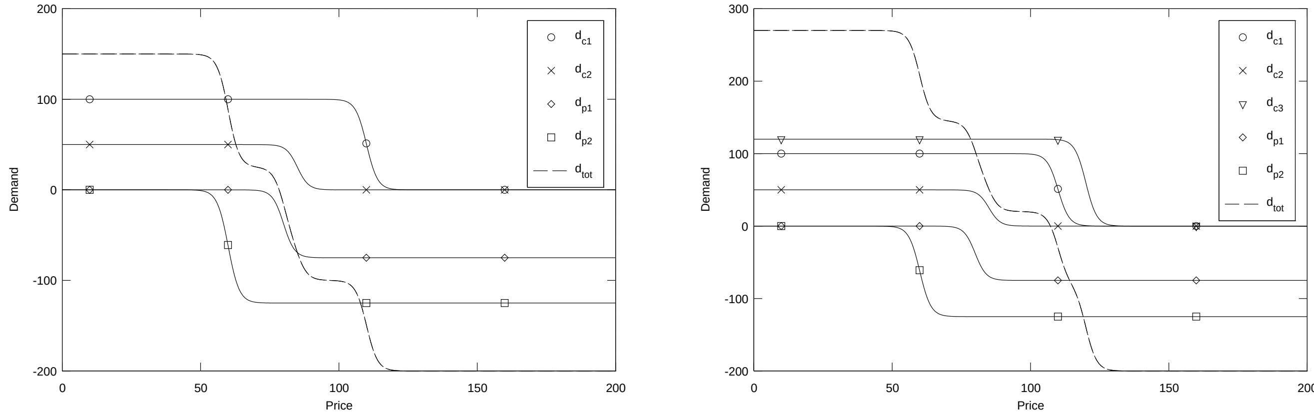
For a number of customers the complexity of a cost-benefit analysis and a market forecast is not acceptable. They are interested in delegating this, e.g. to an energy broker. When multiple energy brokers are available another market on top of the simple centralized market evolves. To take these kinds of changes into account the Catallaxy-based market model allows different kinds of negotiations at different points in time. Although the complexity of these models increase considerably compared to markets with predefined intervals and a single type of auction, it approaches the behavior of real markets to a greater extent.

One example for a real market is the European Energy Exchange (EEX). Here, only around 15% of the electricity consumed within the market area is traded in the day-ahead auctions over the EEX [13]. This number increased over the last years. However, the major amount of electricity is traded in bilateral contracts. According to [13] most of these transactions are on longer terms.

IV. An Example for the Spontaneous Order

A full implementation of a Catallaxy-based market does not exist so far. However, some building blocks are already available. One of them is a distributed market for the resource layer as described in this section. At the resource layer brokers behave like customers and trade with producers for electricity. The contracted power allocations are used on the service layer to combine them to complex services for end-users.

In the following we exemplify how a distributed coordination of the market participants converges to a market equilibrium that fulfills a global objective, e.g. maximizes consumer surpluses. It demonstrates how market participants are self-organizing and presents an example for the spontaneous order of a Catallaxy-based market. Furthermore, we ensure incentives for the participants such that any deviation from this distributed coordination strategy results in a reduction of surplus. Hence, even when participants behave selfish a fair allocation between customers is reached. In the following we introduce a mathematical model for balancing supply and demand in power systems and present a distributed algorithm that ensures the balancing.



(a) $t = t_1$ (b) $t = t_2$

Fig. 2. Example for a Walrasian auction for two energy producers and a changing number of energy customers

Consider a power system consisting of a set of producers $\mathcal{P}$ and the set of consumers[2] $\mathcal{C}$. Denote the capacity of a producer $p \in \mathcal{P}$ as $C_p(t)$. According to Hayek's assumption that no entity has global knowledge but negotiates with different market participants, a producer is not aware of all consumers and vice versa. We define the set of producers, with which customer $c \in \mathcal{C}$ negotiates with $\mathcal{P}(c)$. The other way around $\mathcal{C}(p)$ is the set of the known consumers of the producer p. Furthermore, if $c \in \mathcal{C}(p)$ then also $p \in \mathcal{P}(c)$ holds.

Suppose the utility of a customer c is defined by a utility function U_c, which depends on the total power allocation y_c. Furthermore, the total power allocation is aggregated over power allocations negotiated between a producer and customer (denoted for producer p and customer c as $x_{pc}(t)$). Hence, the optimization problem for the power system is

$$\text{POWER BALANCING MODEL}:$$

$$\text{maximize} \quad \sum_{c \in \mathcal{C}} U_c(y_c(t)) \tag{1}$$

$$\text{subject to} \quad \sum_{p \in \mathcal{P}(c)} x_{pc}(t) = y_c(t), \quad \forall c \in \mathcal{C} \tag{2}$$

$$\sum_{c \in \mathcal{C}(p)} x_{pc}(t) = C_p(t), \quad \forall p \in \mathcal{P} \tag{3}$$

$$\text{over} \quad x_{pc}(t) \geq 0. \tag{4}$$

Maximizing the aggregated utility of the allocation $y_c(t)$ over all consumers is the objective of the whole system, where $y_c(t)$ is the total of the allocations $x_{pc}(t)$ of all producers p of c. This problem is constrained by the capacity at the producers.

In previous work we developed a distributed algorithm for logarithmic utility functions in the field of communication networks [14], [15]. With logarithmic utility functions any power allocation is consumed by the user. However, it implies a diminishing marginal utility: As more and more power is allocated to a user, allocating additional amounts will yield smaller and smaller additions to utility. Although this might be unrealistic for a single load as outlined in Section III, it may apply for an energy broker. For a single load with an inelastic demand sigmoid utility functions can be used. This is shown in [16] for a similar problem for the resource allocation in the Internet.

In the following examples, we assume that all consumers have a logarithmic utility function weighted by their willingness-to-pay W_c of

$$U_c = W_c \log y_c. \tag{5}$$

Since the utility function in (5) is concave and strictly increasing, the optimization problem in (1)–(4) has a unique optimum with respect to the total service rate y_c. However, the rates x_{pc} are not necessarily unique at the optimum, because different rate allocations may sum up to the same total download rate y_c. Thus, many possible rate allocations may exist with respect to x_{pc}.

The global optimization problem can be divided into subproblems for each producer and each customer. These are derived from the Lagrange function (or *Lagrangian*). The Lagrangian is composed by the objective and the constraints of the optimization problem. Constraints are internalized by sums weighted by the Lagrange multipliers. Lagrange functions are frequently used in economic theory, where the behavior of different market participants is modeled as a constrained optimization problem [17]. In this context, Lagrange multipliers are also denoted as shadow prices, because they express the price for an additional unit of the limited resource [18].

To solve the optimization problem in (1)–(4) we propose the distributed algorithm in Algorithm 1. It is derived from the Lagrangian of the problem. A customer sets its willingness-to-pay W_c and computes an offered price λ_c per unit of power in (6). The producer allocates its generated power depending on these prices in (7). Since λ_c is the price per unit of power, the product $x_{pc}\lambda_c$ is the total price which is paid by consumer c. Hence, the sum over all consumers in the denominator of (7) represents the total revenue of producer p. The ratio between the revenue per customer and the total revenue determines the fraction for this customer. This fraction is scaled by the capacity of the producer to get the absolute

[2] At the resource layer energy brokers are the consumers.

Algorithm 1 Distributed Bargaining Algorithm

$$\text{Customer } c:$$
$$\lambda_c(t+1) = \frac{W_c}{\max\left(\eta, \sum_{p\in\mathcal{P}(c)} x_{pc}(t)\right)} \tag{6}$$
$$\text{Producer } p:$$
$$x_{pc}(t+1) = \max\left(\epsilon, x_{pc}(t)\,(1-\bar{\gamma}) + \bar{\gamma}\frac{x_{pc}(t)\lambda_c(t)}{\sum_{d\in\mathcal{C}(p)(t)} x_{pd}(t)\lambda_d(t)} C_p\right) \tag{7}$$

value. To ensure stability energy allocations in (7) are determined as exponential moving average. Although delays are not stated explicitly in Algorithm 1 it is based on asynchronous updates. This means, each producer and each customer is free to decide when to recompute power allocations and offered prices, respectively. This model reflects a market for energy where prices balance the power allocations. Since power can not be stored in the power grid the market is a spot market, where the current demand influences the future prices.

In a well-connected market price offers and power allocations in steady-state are

$$y_c^* = \sum_{p\in\mathcal{P}(c)} x_{pc}^* = \frac{W_c \sum_{p\in\mathcal{P}} C_p(t)}{\sum_{d\in\mathcal{C}} W_d} \tag{8}$$

and

$$\lambda_c^* = \frac{\sum_{d\in\mathcal{C}} W_d}{\sum_{p\in\mathcal{P}} C_p}, \tag{9}$$

respectively.

In the following we present two examples for the distributed algorithm. In the first example the market is well connected and the market equilibrium in (8) and (9) is reached. In the second example fewer connections between producers and customers exist and market equilibrium is not reached. The setup of both examples is similar: Ten producers and ten customers are participating in the market. Each producer and each customer has a capacity and a willingness-to-pay of $C = 100$ and $W = 100$, respectively. This means, in steady state each customer gets a power allocation equal to its willingness-to-pay. The two examples are only different in the number of negotiations between producers and customers. The results of the two examples are depicted in Figure 3 and Figure 4.

In Figure 3 each customer has power allocations with multiple producers and vice versa. Hence, all customers receive the same power allocation for their willingness-to-pay and all producers realize the same revenue. This is different in Figure 4. Here, some customers (i.e. $C10$, $C11$) are served by a single producer. Both customers get a smaller allocation compared to their willingness-to-pay. On the other hand, $C13$ receives a over-proportional allocation because it is served by some producers (i.e. $P3$, $P9$) exclusively.

These examples show that each market participant has to look for alternative trading partners. In an implementation of a protocol this can be realized by starting negotiations with other participants continually. This is similar to P2P networks like BitTorrent [19], where each peer maintains a list of other peers in the network. This list is updated from time to time. Furthermore, a peer selection algorithm chooses the best trading partners at the moment. However, also an exception is run and negotiations are started with new peers independently of the current state.

V. Conclusion

Market-oriented models are used for balancing supply and demand in power systems. Different models are proposed in the literature. To the best of our knowledge these models rely on some kind of centralized coordination, e.g. auction platforms or order books. These centralized market platforms define the rules for bidding on the market. These rules might not be applicable for all market participants. Hence, we propose in this paper a free market approach called Catallaxy. Here, market participants are self-organizing and negotiate with different other participants. Power is contracted bilaterally. However, participants look for alternative trading partners. Thus, as demonstrated by simulations market equilibrium evolves.

To offer different kinds of services a two-tier architecture is proposed, where energy brokers trade energy on small time scales and assemble complex services to customers. This has different advantages: Energy brokers make use of the multiplexing effect of different customers. The variance in demand for a single customer is flattened by the others. Hence, energy brokers can offer allocation bundles for different time periods and fuzzy demands to customers.

Because of its complexity a full realization of Catallaxy-based markets does not exist so far, this paper presents the architecture and a distributed control algorithm. Future work will study the two-tier architecture in more detail and looks at markets with different types of negotiations.

References

[1] S. McArthur, E. Davidson, V. Catterson, A. Dimeas, N. Hatziargyriou, F. Ponci, and T. Funabashi, "Multi-agent systems for power engineering applicationspart i: Concepts, approaches, and technical challenges," *IEEE Transactions on Power Systems*, vol. 22, no. 4, pp. 1743 – 1752, Nov. 2007.

[2] A. Dimeas and N. Hatziargyriou, "Operation of a multiagent system for microgrid control," *IEEE Transactions on Power Systems*, vol. 20, no. 3, pp. 1147–1455, Aug. 2005.

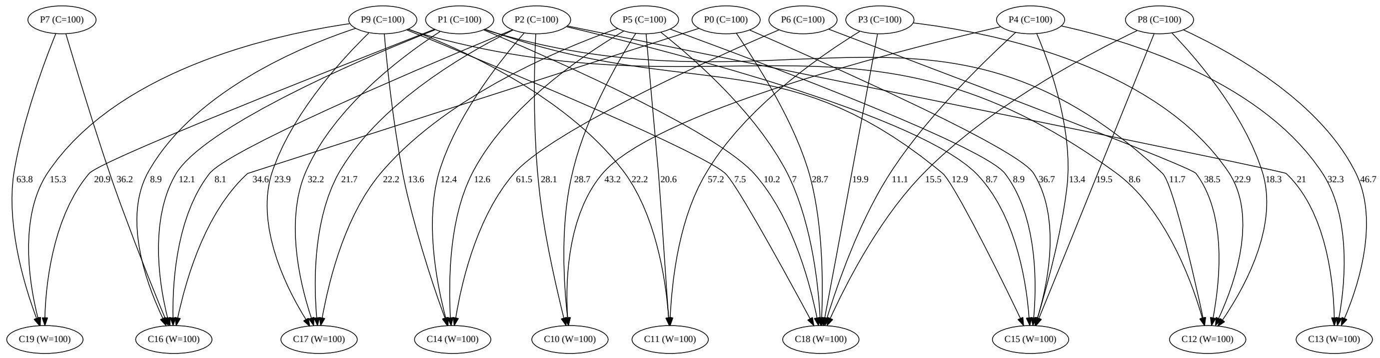


Fig. 3. Example 1: Well-connected market where equilibrium is reached

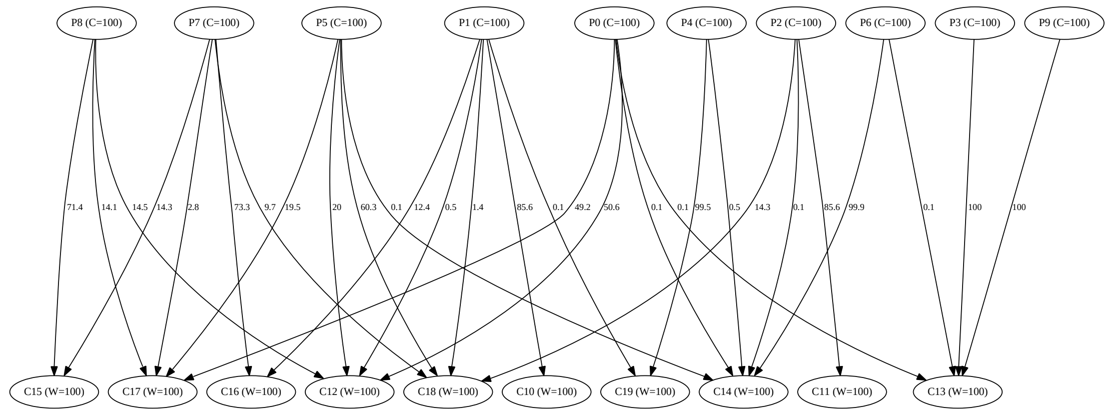


Fig. 4. Example 2: Sparesly-connected market where equilibrium is not reached

[3] M. Hommelberg, B. van der Velde, C. Warmer, I. Kamphuis, and J. Kok, "A novel architecture for real-time operation of multi-agent based coordination of demand and supply," in *IEEE Power and Energy Society General Meeting - Conversion and Delivery of Electrical Energy in the 21st Century*, Jul. 2008, pp. 1–5.

[4] J. Kok, C. Warmer, and I. Kamphuis, "Powermatcher: multiagent control in the electricity infrastructure," in *Proc. Fourth International Joint Conference on Autonomous Agents and Multiagent Systems (AAMAS05)*, July 2005.

[5] C. Block, D. Neumann, and C. Weinhardt, "A market mechanism for energy allocation in micro-chp grids," in *Proc. of the 41st Annual Hawaii International Conference on System Sciences*, Jan. 2008.

[6] F. Hayek, *Law, Legislation and Liberty, Volume 2: The Mirage of Social Justice*. University Of Chicago Press, 1978.

[7] A. Oram, Ed., *Peer to Peer: Harnessing the Power of Disruptive Technologies*. O'Reilly, 2001.

[8] M. Conrad, J. Dinger, H. Hartenstein, D. Rolli, M. Schöller, and M. Zitterbart, "A Peer-to-Peer Framework for Electronic Markets," in *Peer-to-Peer Systems and Applications*, R. Steinmetz and K. Wehrle, Eds. Springer LNCS 3485, Sep. 2005, pp. 509–525.

[9] H. Beitollahi and G. Deconinck, "Peer-to-peer networks applied to power grid," in *the International conference on Risks and Security of Internet and Systems (CRiSIS) in conjunction with the IEEE GIIS'07*, Marrakech, Morocco, Jul. 2007.

[10] T. Eymann, M. Reinicke, W. Streitberger, O. Rana, L. Joita, D. Neumann, B. Schnizler, D. Veit, O. Ardaiz, P. Chacin, I. Chao, F. Freitag, L. Navarro, M. Catalano, M. Gallegati, G. Giulioni, R. C. Schiaffino, and F. Zini, "Catallaxy-based grid markets," *Multiagent Grid Syst.*, vol. 1, no. 4, pp. 297–307, 2005.

[11] I. Foster and C. Kesselman, *The Grid 2: Blueprint for a New Computing Infrastructure*. Morgan Kaufmann, November 2004.

[12] K. Kok, Z. Derzsi, J. Gordijn, M. Hommelberg, C. Warmer, R. Kamphuis, and H. Akkermans, "Agent-based electricity balancing with distributed energy resources, a multiperspective case study," in *HICSS '08: Proceedings of the Proceedings of the 41st Annual Hawaii International Conference on System Sciences*, 2008.

[13] A. Ockenfels, V. Grimm, and G. Zoettl, "Electricity market design - the pricing mechanism of the day ahead electricity spot market auction on the EEX," Mar. 2008. [Online]. Available: http://www.eex.com/de/document/38615/gutachten_eex_ockenfels_e.pdf

[14] K. Eger and U. Killat, "Resource pricing in peer-to-peer networks," *IEEE Communications Letters*, vol. 11, no. 1, pp. 82–84, Jan. 2007.

[15] ——, "Fair resource allocation in peer-to-peer networks (extended version)," *Computer Communications, Special Issue: Advances in Communication Networking, Elsevier*, vol. 30, no. 16, pp. 3046–3054, Nov. 2007.

[16] J.-W. Lee, R. Mazumdar, and N. Shroff, "Non-convex optimization and rate control for multi-class services in the internet," *IEEE/ACM Transactions on Networking*, vol. 13, no. 4, pp. 827– 840, Aug. 2005.

[17] R. S. Pindyck and D. L. Rubinfeld, *Microeconomics*, 6th ed. Pearson Prentice Hall, 2005.

[18] S. Boyd and L. Vandenberghe, *Convex Optimization*. Cambridge University Press, 2006.

[19] B. Cohen, "Incentives build robustness in BitTorrent," in *Proc. 1st Workshop on Economics of Peer-to-Peer Systems*, Berkeley, Jun. 2003.