Fair Pricing for Time-Flexible Smart Energy Markets

Extended Abstract

Roland Saur
Centrum Wiskunde & Informatica
Amsterdam, The Netherlands
TU Delft
Delft, The Netherlands
Roland.Saur@cwi.nl

Han La Poutré
Centrum Wiskunde & Informatica
Amsterdam, The Netherlands
TU Delft
Delft, The Netherlands
Han.La.Poutre@cwi.nl

Neil Yorke-Smith
STAR Lab, TU Delft
Delft, The Netherlands
n.yorke-smith@tudelft.nl

ABSTRACT

The adoption of new market mechanisms – vital to the better integration of flexible assets – depends on the fairness and non-discrimination of the pricing rules. We consider a market setting with time-flexible unit energy buyers and sellers, that additionally submit their availability in time. The time-flexibility of the agents allows for different schedules to be equivalent with regard to social welfare, which can lead to arbitrary price differences, i.e. price discrimination. In this work, we demonstrate that non-discriminatory prices are not trivially defined in time-flexible settings, provide a definition of non-discrimination as consistent over equivalent outcomes, show that this concept does not conflict with individual rationality and, finally, compare our work to broader concepts of fairness from economic psychology.

KEYWORDS

Auctions; Mechanism Design; Discrimination; Energy Markets

ACM Reference Format:
Roland Saur, Han La Poutré, and Neil Yorke-Smith. 2023. Fair Pricing for Time-Flexible Smart Energy Markets: Extended Abstract. In *Proc. of the 22nd International Conference on Autonomous Agents and Multiagent Systems (AAMAS 2023), London, United Kingdom, May 29 – June 2, 2023*, IFAAMAS, 3 pages.

1 INTRODUCTION AND MOTIVATION

Large investments in renewable energies [43, 46] and the electrification of the transportation sector [40, 43, 47] are putting enormous stress on the electricity grid [22]. To handle this burden without unrealistic investment in grid reinforcement, research has pushed towards a tighter integration of flexible assets into electricity systems [6, 14, 18], such as fleets of electric vehicles [39], groups of thermostatically controlled loads [37] or household batteries [1].

New market mechanisms [31, 34, 41, 48] promise better integration of such flexible assets. However, early approaches, relying on time-dependent dynamic prices [24], are often not sufficient [8], which led to the development of markets in which agents instead of deciding for themselves when to operate simply provide their flexibility information to a market operator [8].

Flexibility information can be communicated in different ways. In duration-differentiated energy services, agents report a time window in which they are indifferent to the exact delivery, as well as the duration of their energy demand. In other works, agents report time windows in which their load can be rescheduled [14, 20] or express their flexibility as XOR bids [45]. As the goal of our work is to address a fundamental property, we consider a stylized market in which unit demand agents report time windows, which can be viewed as XOR bids and differ from the duration-differentiated energy services only in that the duration is restricted to a single time step.

The effectiveness of a energy markets depends on adoption by people [13] and therefore social acceptance, which is heavily influenced by a perception of fairness [19, 21, 32, 44]. Such a perception of fairness is often tied to pricing [30], which in the energy domain has mostly revolved around fairness in real time [29] or time-of-use pricing systems [6, 28]. Fair price sharing for flexible demand profiles has been investigated in Perrault and Boutilier [35]. However, few have specifically focused on fair pricing in time flexible systems. One exception is Limmer and Dietrich [25], who consider fairness in flexible-in-time electric vehicles by looking at price fluctuations over time. However, we actually define the concept of non-discriminatory pricing in such a system.

The concept of non-discriminatory or anonymous pricing has been explored in the mechanism design literature by Sandholm and Suri [38] with regard to market clear-ability, while Conen and Sandholm [12] explored under which conditions item or bundle prices support optimal allocations. Approximation guarantees of posted prices have been established [15] as well as guarantees for revenue maximization of anonymous pricing [2].

In contrast, we will address the question of *what constitutes price discrimination itself*, and when differences in prices for ostensibly the same item are justified. We will explore this question in the context of energy markets with flexible-in-time participants.

2 SETTING AND DESIRED PROPERTIES

Consider a set of flexible unit buyer and seller agents $N = B \cup S$. Each agent $n \in N$ has a time window τ_n in which it can operate. Every agent operates for a single time step. Every buyer $b \in B$ assigns valuation v_b to being allocated, while every seller $s \in S$ incurs cost c_s when allocated. The market collects reports Θ_n from agents $n \in N$. A buyer b reports $\Theta_b = (\tau_b, v_b)$, which contains its time window τ_b and its valuation v_b. Similarly, a seller s reports $\Theta_s = (\tau_s, c_s)$. We define a buyer–seller pair $\{b, s\}$ and associate it with an operating window $\tau_{b,s} = \tau_b \cap \tau_s$. We say a buyer–seller pair $\{b, s\}$ is feasible if the buyer and seller time windows overlap, i.e., $\tau_b \cap \tau_s \neq \emptyset$. Further, we say that two different buyer–seller pairs, $\{b_1, s_1\}$ and $\{b_2, s_2\}$ are in conflict if one agent appears in both pairs, i.e., $b_1 = b_2 \lor s_1 = s_2$. A *matching* M is a set of buyer–seller pairs.

Proc. of the 22nd International Conference on Autonomous Agents and Multiagent Systems (AAMAS 2023), A. Ricci, W. Yeoh, N. Agmon, B. An (eds.), May 29 – June 2, 2023, London, United Kingdom.

A matching M is feasible if all buyer–seller pairs in M are feasible and no pairs are conflicting. Social welfare $SW(M)$ of a matching is defined as the sum of gains from trade. Beside maximizing SW, which can be done in polynomial time [23], we desire prices, $p()$, that are Budget Balanced (BB), Individually Rational (IR) and non-discriminatory – the meaning of which we will explore here.

3 CONSISTENT PRICING OVER EQUIVALENT OUTCOMES

Because of the flexibility of the agents, there exist many different matching that are SW maximizing. We call two matchings that result in the same social welfare equivalent. When a pricing function depends on the particular configuration of a matching, it means a market operator can pick one matching among equivalent matchings that benefits some agents at the cost of others. To prevent a market operator from such discrimination between agents, we require prices that only depend on the overall SW and not on any particular matching.

Towards this aim, we introduce a computationally cheap way of representing all equivalent matchings (Lemma 3.1), use it to identify identically-priced agents (Lemma 3.2) and finally show that our approach can also provide Individually Rational prices (Theorem 3.3).

The computationally cheap representation, is a directed graph $H_M = (V, E)$, in which nodes V represent the pairs of the original matching M and edges E represent possible alternative pairs.

We see that any equivalent matching has a corresponding representation in graph H_M in the form of non-overlapping cycles.

Lemma 3.1 (Cycles form equivalent matchings). *A matching $M^\dagger$ is equivalent to M if and only if there exists a set of non-overlapping simple cycles Z in H_M such that (V_{-Z}, E_Z) forms $M^\dagger$ where E_Z is the set of edges in the cycles Z and $V_{-Z} = V \setminus \bigcup E_Z$.*

Given that all M-equivalent matchings are represented in the directed graph H_M, we can identify the groups of agents that are priced identically by a non-discriminatory pricing function. Since equivalent matchings are represented by cycles, a non-discriminatory pricing function will assign the same price to agents within the same strongly connected component in graph H_M.

Lemma 3.2 (Price sharing agents). *Given a matching M, a consistent pricing function p assigns the same price to two buyer–seller pairs $\{b_x, s_x\}$ and $\{b_y, s_y\}$ if and only if v_x and v_y are part of the same strongly connected component in the graph H_M.*

Having identified these groups of identically priced agents, we show that our concept of consistent pricing does not conflict with Individually Rational pricing.

Theorem 3.3 (Existence of consistent, IR Prices). *Given a SW-maximizing matching M there exist consistent prices that are Individual Rationality.*

Because we assign prices to pairs, the budget is always balanced.

4 DISCUSSION: CONSISTENT PRICING, ENVY-FREENESS AND FAIRNESS

Fairness is a vague, intuitive human term. However, in order to design systems, we (humans) require precise definitions and have therefore come up with specific mathematical concepts to represent our human intuition.

One of the strongest fairness concepts is envy-freeness [7, 10, 27, 36]. However, due to the difficulty of achieving full envy-freeness, several relaxations have been proposed. Our concept of consistent pricing can be viewed as a new kind of relaxation of envy-freeness.

We will first explain how our concept of fairness relates to broader fairness concepts from economic psychology and then compare it to other relaxations of envy-freeness.

In economic psychology, there exist two notions of fairness in pricing. *Distributed justice* states that agents perceive prices as fair, if they are in line with their reference price [9, 26, 30], e.g., historical or the prices of others. *Procedural justice*, on the other hand, says that prices are seen as fair by agents, if the agents know that the process of obtaining the price was fair itself [9, 26, 30].

In the context of economic psychology, envy-freeness can be viewed as distributed justice – no agent sees another agent being paid better or worse – while our concept of consistent prices reflect the procedural justice notion – the intention of the pricing process was to be non-discriminatory, i.e., a form of fairness.

These concepts of procedural and distributed justice are not in conflict with each other, but rather represent two aspects of how humans perceive fairness with envy-freeness and consistent pricing being mathematical representations thereof.

4.1 Comparison to relaxations of envy-freeness

Relaxations on the concept of envy-freeness allow either for a particular kind [3, 4, 16, 17, 42] or magnitude of envy [7, 10, 27, 36]. The concept put forth in this paper allows for a particular kind rather than magnitude of envy. Envy is restricted to settings, in which the desired alternative comes at a cost to social welfare.

With regard to relaxing envy-freeness by a certain magnitude, the field of fair division provides the concept of "Envy-freeness up to any good" [7, 10, 27, 36].

When it comes to restricting a particular kind of envy, group envy-freeness [3, 42] restricts envy to particular groups of agents, while social graphs have been used to indicate an agent's awareness of other prices [4, 16, 17].

However, group envy freeness is only applicable in specific settings, while the use of a social graph to restrict which agents can envy each other betrays the original idea of fairness.

An agent, who has arbitrarily been given a worse deal is not treated fairly simply because it is not aware of the better deal. This is also corroborate by studies in economic psychology, which state that, especially in the absence of price difference, a sense of fairness is established via procedural justice [5, 9]. The fairness perception of an agent who is not aware of other prices in the system is more strongly influenced by the way prices are derived.

ACKNOWLEDGMENTS

The authors thanks the anonymous AAMAS reviewers. This work is part of the research project Heat and Power Systems at Industrial Sites and Harbours (HaPSISH) with project number OND1363719, and partly financed by the Dutch Research Council (NWO).

REFERENCES

[1] Christopher O. Adika and Lingfeng Wang. 2014. Non-Cooperative Decentralized Charging of Homogeneous Households' Batteries in a Smart Grid. *IEEE Transactions on Smart Grid* 5, 4 (jul 2014), 1855–1863. https://doi.org/10.1109/tsg.2014.2302449

[2] S. Alaei, J. Hartline, Rad Niazadeh, Emmanouil Pountourakis, and Y. Yuan. 2015. Optimal Auctions vs. Anonymous Pricing. *2015 IEEE 56th Annual Symposium on Foundations of Computer Science* (2015), 1446–1463.

[3] Martin Aleksandrov and Toby Walsh. 2018. Group envy freeness and group pareto efficiency in fair division with indivisible items. In *Joint German/Austrian Conference on Artificial Intelligence (Künstliche Intelligenz)*. Springer, 57–72.

[4] Noga Alon, Yishay Mansour, and Moshe Tenneholtz. 2013. Differential pricing with inequity aversion in social networks. In *Proceedings of the fourteenth ACM conference on Electronic commerce*. 9–24.

[5] Laurence Ashworth and Peter R. Darke. 2006. The Principle Matters: Antecedents and Consequences of Procedural Justice in the Context of Pricing. *ACR North American Advances* (2006).

[6] Khursheed Aurangzeb, Sheraz Aslam, Syed Muhammad Mohsin, and Musaed Alhussein. 2021. A Fair Pricing Mechanism in Smart Grids for Low Energy Consumption Users. *IEEE Access* 9 (2021), 22035–22044.

[7] Xiaohui Bei, Xinhang Lu, Pasin Manurangsi, and Warut Suksompong. 2021. The price of fairness for indivisible goods. *Theory of Computing Systems* 65, 7 (2021), 1069–1093.

[8] Eilyan Bitar and Steven Low. 2012. Deadline differentiated pricing of deferrable electric power service. In *2012 IEEE 51st IEEE Conference on Decision and Control (CDC)*. 4991–4997. https://doi.org/10.1109/CDC.2012.6425944

[9] Jean Michel Chapuis. 2012. Price Fairness Versus Pricing Fairness. https://doi.org/10.2139/ssrn.2015112

[10] Bhaskar Ray Chaudhury, Telikepalli Kavitha, Kurt Mehlhorn, and Alkmini Sgouritsa. 2021. A Little Charity Guarantees Almost Envy-Freeness. *SIAM J. Comput.* 50, 4 (2021), 1336–1358. https://doi.org/10.1137/20M1359134 arXiv:https://doi.org/10.1137/20M1359134

[11] Wei Chen, Li Qiu, and Pravin Varaiya. 2015. Duration-deadline jointly differentiated energy services. In *2015 54th IEEE Conference on Decision and Control (CDC)*. IEEE. https://doi.org/10.1109/cdc.2015.7403358

[12] W. Conen and T. Sandholm. 2004. Anonymous pricing of efficient allocations in combinatorial economies. *Proceedings of the Third International Joint Conference on Autonomous Agents and Multiagent Systems, 2004. AAMAS 2004.* (2004), 254–260.

[13] O. Ellabban and H. Abu-Rub. 2016. Smart grid customers' acceptance and engagement: An overview. *Renewable & Sustainable Energy Reviews* 65 (2016), 1285–1298.

[14] Ayman Esmat, J. Usaola, and M. A. Moreno. 2018. Distribution-Level Flexibility Market for Congestion Management. *Energies* 11 (2018), 1056.

[15] Michal Feldman, Nick Gravin, and Brendan Lucier. 2014. Combinatorial auctions via posted prices. In *Proceedings of the twenty-sixth annual ACM-SIAM symposium on Discrete algorithms*. SIAM, 123–135.

[16] Michele Flammini, Manuel Mauro, and Matteo Tonelli. 2021. On fair price discrimination in multi-unit markets. *Artificial Intelligence* 290 (2021), 103388.

[17] Michele Flammini, Manuel Mauro, Matteo Tonelli, and Cosimo Vinci. 2020. Inequity aversion pricing in multi-unit markets. In *24th European Conference on Artificial Intelligence (ECAI)*, Vol. 325. IOS Press, 91–98.

[18] Gilbert Fridgen, Philipp Mette, and Markus Thimmel. 2014. The Value of Information Exchange in Electric Vehicle Charging. In *ICIS*.

[19] S. Guerreiro, Susana Batel, M. L. Lima, and S. Moreira. 2015. Making energy visible: sociopsychological aspects associated with the use of smart meters. *Energy Efficiency* 8 (2015), 1149–1167.

[20] Keiichiro Hayakawa, Enrico H Gerding, Sebastian Stein, and Takahiro Shiga. 2015. Online mechanisms for charging electric vehicles in settings with varying marginal electricity costs. In *Twenty-Fourth International Joint Conference on Artificial Intelligence*.

[21] Nma Nicole Huijts, Eje Eric Molin, and Linda Steg. 2012. Psychological factors influencing sustainable energy technology acceptance: A review-based comprehensive framework. *Renewable & Sustainable Energy Reviews* 16 (2012), 525–531.

[22] Nikolaos E. Koltsaklis and Athanasios S. Dagoumas. 2018. State-of-the-art generation expansion planning: A review. *Applied Energy* 230 (2018), 563–589.

[23] H. Kuhn. 1955. The Hungarian method for the assignment problem. *Naval Research Logistics Quarterly* 2 (1955), 83–97.

[24] Steffen Limmer. 2019. Dynamic Pricing for Electric Vehicle Charging—A Literature Review. *Energies* 12, 18 (sep 2019), 3574. https://doi.org/10.3390/en12183574

[25] Steffen Limmer and Manuel Dietrich. 2018. Optimization of dynamic prices for electric vehicle charging considering fairness. In *2018 IEEE Symposium Series on Computational Intelligence (SSCI)*. IEEE, 2304–2311.

[26] E Allan Lind and Tom R Tyler. 1988. *The social psychology of procedural justice*. Springer Science & Business Media.

[27] Vasilis Livanos, Ruta Mehta, and Aniket Murhekar. 2022. (Almost) Envy-Free, Proportional and Efficient Allocations of an Indivisible Mixed Manna. *arXiv preprint arXiv:2202.02672* (2022).

[28] Ziming Ma, Haiwang Zhong, Qing Xia, and Chongqing Kang. 2019. A block-of-use electricity retail pricing approach based on the customer load profile. *IEEE Transactions on Smart Grid* 11, 2 (2019), 1500–1509.

[29] Ioannis Mamounakis, Nikolaos Efthymiopoulos, Dimitrios J Vergados, Georgios Tsaousoglou, Prodromos Makris, and Emmanouel Manos Varvarigos. 2019. A pricing scheme for electric utility's participation in day-ahead and real-time flexibility energy markets. *Journal of Modern Power Systems and Clean Energy* 7, 5 (2019), 1294–1306.

[30] S. Maxwell. 2002. Rule-based price fairness and its effect on willingness to purchase. *Journal of Economic Psychology* 23 (2002), 191–212.

[31] Reshef Meir, Hongyao Ma, and Valentin Robu. 2017. Contract Design for Energy Demand Response. In *Proceedings of the Twenty-Sixth International Joint Conference on Artificial Intelligence, IJCAI-17*. 1202–1208. https://doi.org/10.24963/ijcai.2017/167

[32] Christine Milchram, G. Kaa, N. Doorn, and R. Künneke. 2018. Moral Values as Factors for Social Acceptance of Smart Grid Technologies. *Sustainability* 10 (2018), 1–23.

[33] Yanfang Mo, Wei Chen, and Li Qiu. 2016. Duration-differentiated energy services with peer-to-peer charging. In *2016 IEEE 55th Conference on Decision and Control (CDC)*. IEEE. https://doi.org/10.1109/cdc.2016.7799430

[34] P. Palensky and D. Dietrich. 2011. Demand Side Management: Demand Response, Intelligent Energy Systems, and Smart Loads. *IEEE Transactions on Industrial Informatics* 7 (2011), 381–388.

[35] Andrew Perrault and Craig Boutilier. 2015. Approximately stable pricing for coordinated purchasing of electricity. In *Twenty-Fourth International Joint Conference on Artificial Intelligence*.

[36] Benjamin Plaut and Tim Roughgarden. 2020. Almost envy-freeness with general valuations. *SIAM Journal on Discrete Mathematics* 34, 2 (2020), 1039–1068.

[37] Ashraf Radaideh and Venkataramana Ajjarapu. 2016. Extracting expedient short term services from Homogeneous Group of Thermostatically Controlled Loads. In *2016 IEEE Power & Energy Society Innovative Smart Grid Technologies Conference (ISGT)*. IEEE. https://doi.org/10.1109/isgt.2016.7781030

[38] Tuomas Sandholm and Subhash Suri. 2001. Market clearability. In *International joint conference on artificial intelligence*, Vol. 17. LAWRENCE ERLBAUM ASSOCIATES LTD, 1145–1151.

[39] Karlo Sepetanc and H. Pandzic. 2021. A Cluster-Based Model for Charging a Single-Depot Fleet of Electric Vehicles. *IEEE Transactions on Smart Grid* 12, 4 (jul 2021), 3339–3352. https://doi.org/10.1109/tsg.2021.3064272

[40] Blake Shaffer. 2019. Energy and Environmental Policy Trends: Will Electric Vehicle Rebates Spur Widespread Adoption? *The School of Public Policy Publications* 12 (2019).

[41] Bochao Shen, Balakrishnan Narayanaswamy, and Ravi Sundaram. 2015. SmartShift: expanded load shifting incentive mechanism for risk-averse consumers. In *Twenty-Ninth AAAI Conference on Artificial Intelligence*.

[42] Taiki Todo, Atsushi Iwasaki, and Makoto Yokoo. 2019. Competitive auctions and envy-freeness for group of agents. In *International Computing and Combinatorics Conference*. Springer, 541–553.

[43] Mohammad Waseem, Ahmad Faizan Sherwani, and Mohd Suhaib. 2019. Integration of solar energy in electrical, hybrid, autonomous vehicles: a technological review. *SN Applied Sciences* 1, 11 (2019), 1–14.

[44] T. D. Wildt, E. J. Chappin, G. Kaa, P. Herder, and I. Poel. 2019. Conflicting values in the smart electricity grid: A comprehensive overview. *Renewable & Sustainable Energy Reviews* 111 (2019), 184–196.

[45] Bizzat Hussain Zaidi and S. Hong. 2018. Combinatorial double auctions for multiple microgrid trading. *Electrical Engineering* 100 (2018), 1069–1083.

[46] Shihong Zeng, Yuchen Liu, Chao Liu, and Xin Nan. 2017. A review of renewable energy investment in the BRICS countries: History, models, problems and solutions. *Renewable and Sustainable Energy Reviews* 74 (2017), 860–872.

[47] Jihu Zheng, X. Sun, Li-Jie Jia, and Y. Zhou. 2020. Electric passenger vehicles sales and carbon dioxide emission reduction potential in China's leading markets. *Journal of Cleaner Production* 243 (2020), 118607.

[48] Ma Zhongjing and R. Long. 2013. Optimal distributed charging coordinations of plug-in electric vehicles with market uniform clearing price mechanism. *2013 25th Chinese Control and Decision Conference (CCDC)* (2013), 3497–3502.