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Extended Abstract

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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

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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., $b_1 = b_2 \vee s_1 = s_2$. A *matching* M is a set of buyer–seller pairs.

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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.

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