Fairness in Smart Grid Congestion Management

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***Abstract*—With the energy transition, grid congestion is increasingly becoming a problem. This paper proposes the implementation of fairness in congestion management by presenting quantitative fair optimization goals and fairness measuring tools. Furthermore, this paper presents a congestion management solution in the form of an egalitarian allocation mechanism. Finally, this paper proves that this mechanism is truthful, pareto efficient, and maximizes a fair optimization goal.**

I. Introduction

The energy system is going through a transition. This energy transition is brought about by an increasing penetration of renewable energy sources and a push towards a more decentralized system. With these developments, congestion on electrical grid lines is becoming a more widespread problem [1]; one that is not easily solved using storage [2]. The intermittent nature of renewable energy resources, the decentralized nature of consumers and producers (often *prosumers* now), and the intensive disruptive demand introduced by electric vehicles and heat pumps all contribute to grid congestion issues. According to a study concerning the German electrical grid; "over the past five years, the costs for congestion management and curtailment have increased by a factor of ten, to about one billion euro per year." [3].

Grid congestion management solutions appear in various forms and address different aspects of grid congestion problems [4], [5], [6], [7], [8]. However, while grid constraints raise questions concerning priority when conflicts of use arise, these studies on congestion management do not take into account an explicit notion of fairness. A recent package of measures presented by the European Commission states that "energy is a critical good, absolutely essential for full participation in modern society. The clean energy transition also needs to be fair for those sectors, regions or vulnerable parts of society affected by the energy transition." [9]. In light of this statement, the incorporation of fairness is left insufficiently covered by grid congestion management research.

The incorporation of fairness in grid congestion management is no straightforward task. Notions of fairness are fundamentally subjective, and accepted notions of fairness do not necessarily translate from one setting to another. Moreover, other goals such as efficiency may take precedence over fairness, limiting the scope of fairness that can be implemented. Once a notion of fairness has been accepted for a certain setting, it can serve one or more of the following three main uses:

- As a binary descriptor; it is expressed qualitatively and its definition either is or is not satisfied by a situation.
- As a tool for maximizing fairness; it is expressed quantitatively and may be used as an optimization goal for fairness and other qualities.
- To compare and evaluate situations; it is expressed quantitatively, preferably normalized, and measures fairness independent of other qualities.

This paper proposes two implementations of fairness suitable for congestion management in electrical grids. Both of these implementations will be of the quantitative type and may be used as an optimization goal or a measure of fairness. The first implementation of fairness that this paper proposes is based on the Nash product that was introduced by Nash [10] and closely resembles the notion of social welfare. The second implementation of fairness that this paper proposes is based on research in behavioral economics by Fehr and Schmidt [11], and mimics the inequity-based comparative utility (inequality between agents negatively affects their utilities) that is observed in humans.

Furthermore, this paper presents a congestion management solution in the form of an egalitarian allocation mechanism. Based on consumer data, this mechanism allocates consumption limits to individual consumers in order to resolve congestion in acyclic networks. Finally, this paper proves that the presented mechanism is truthful and maximizes both the social welfare and Nash product.

II. Setting and Notation

Consider a network $\mathcal{N}$, represented by a graph (N, L). Prosumers p, i.e. agents that may either produce or consume at any given time, are located at the vertices $n \in N$ called nodes. The edges represent electrical grid lines $l \in L$ with positive capacity constraints C_l that constrain the power flow over the line l. A connection to an external network may be represented by an edge associated with only one vertex. Prosumption of a prosumer p is represented by an activity a_p, with positive and negative activity corresponding to consumption and production respectively. Let P denote the set of all prosumers in the network, and let P^+ and P^- denote the subsets of consumers and producers, respectively.

When congestion occurs, i.e. at least one of the line capacity constraints C_l is exceeded by the power flow over that line, a congestion management mechanism resolves the congestion. It does so by finding an allocation A: a set of activities a_p for

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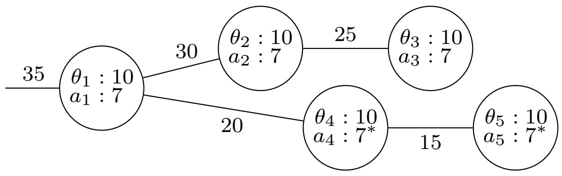

Fig. 1. An example network of five prosumers. Allocation 1 is as shown, while allocation 2 differs by instead setting $a_4 = 9$ and $a_5 = 5$.

the prosumers $p \in P$. As a result, for some prosumers p, there will be a difference between the prosumer's reported desired activity, referred to as the type θ_p, and its final activity a_p. A reported desired consumption, i.e. $\theta_p > 0$, must always result in a final activity $0 \leq a_p \leq \theta_p$. Similarly for production.

Each prosumer p has a utility function u_p that depends on the activity a_p, the valuation of the activity $v_p(a_p)$, the price of the activity $\lambda_p(a_p)$, and the type θ_p. This paper assumes a setting in which, for a network of limited size, the price function λ_p is identical for all prosumers p and scales linearly with the activity a_p. Furthermore, the valuation function v_p is identical for all prosumers p and scales linearly with the activity a_p. Therefore, in this setting, the utility function u_p only depends on at most the activity a_p and type θ_p.

III. Fairness Optimization and Measurement

A common way to optimize allocations of a divisible good to a set of agents, is to maximize the social welfare (*SW*). This means maximizing the sum over all agents' utilities:

$$\max_{A \in \mathcal{S}} \sum_{P} u_p(A). \tag{1}$$

Here, $\mathcal{S}$ denotes the solution set: the set of allocations that resolve congestion and assign consumption and production exclusively to consumers and producers respectively, bounded by their types, as described in Section II.

Since fairness is an inter-agent concept, *SW* cannot take fairness into consideration without explicitly incorporating it in the individual utility functions; Section IV further considers this option.

An alternative optimization goal is the Nash product (*NP*):

$$\max_{A \in \mathcal{S}} \prod_{P} u_p(A). \tag{2}$$

This optimization problem, like the *SW* optimization in (1), maximizes all prosumers' utilities, within $\mathcal{S}$. However, unlike in (1), the *NP* optimization in (2) also maximizes the minimal utility among prosumers, within $\mathcal{S}$. The differences are illustrated with the help of a running example, shown in Figure 1. Taking the simplest utility function for each prosumer p, i.e.

$$u_p = |a_p|, \tag{3}$$

the *SW* and *NP* values associated with the two allocations presented in Figure 1 are displayed in Table I. Table I shows that the *SW* approach does not differentiate between the two allocations, while the *NP* takes a higher value when the allocated activities are closer to each other. Note that both allocations yield the same total consumption.

		Allocation 1	Allocation 2
SW	$\sum \lvert a_p \rvert$	35	35
NP	$\prod \lvert a_p \rvert$	16807	15435
ASW	$\frac{1}{n} \sum \lvert a_p \rvert$	7	7
ANP	$\sqrt[n]{\prod \lvert a_p \rvert}$	7	6.88
NNP	$\sqrt[n]{\prod a_p / \theta_p}$	0.7	0.69

TABLE I
Social welfare and Nash product values for the two allocations presented in Figure 1.

In order to have the *SW* and *NP* not only serve as an optimization goal but also as a measure, i.e. an indicator independent of irrelevant qualities, the average is taken. This eliminates their dependency on the size of the system. For the average Nash product (*ANP*), the optimization then takes the following form:

$$\max_{A \in \mathcal{S}} \sqrt[n]{\prod_{P} u_p(A)}, \tag{4}$$

where n is the number of prosumers in P. Note that taking the average does not affect the optimization problem. The values of the averaged social welfare (*ASW*, see Table I) and *ANP* on the two allocations presented in Figure 1 are also displayed in Table I.

The *ANP*, however, still depends on the absolute level of prosumption. This dependency can be removed by considering utility functions that reflect the relative activity instead of the absolute activity, that is

$$u_p = a_p / \theta_p. \tag{5}$$

This results in the normalized Nash product (*NNP*) that takes values between 0 and 1. Since the *NNP* is largely independent of qualities other than fairness, it is well suited as a measure of fairness. The values that the *NNP* takes on the two allocations presented in Figure 1 are displayed in Table I as well.

The downside of the relative utility function (5) is that its value is influenced to a large extent by the type of the prosumer. This means that a prosumer p intentionally reporting a large type θ_p affects the value of the *ANP* significantly. Moreover, it skews the optimization problem to allocate a potentially disproportionate amount of activity to such a prosumer p. Thus, while the *NNP* provides a fine measuring tool, the absolute utility function (3) is better suited as an optimization goal.

IV. Comparative Utility and Network Topology

An alternative approach to incorporating fairness in congestion management, is to explicitly include a notion of fairness in the individual utility functions of the prosumers p. Research in behavioral economics by Fehr and Schmidt [11]

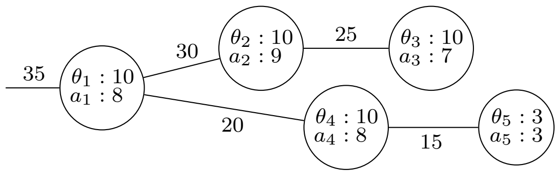

Fig. 2. The example network with the type of one prosumer lowered.

proposes a model aimed at capturing fairness-related behaviour in humans, specifically inequity-aversion. Their findings can be used to construct utility functions for software agents that closely resemble the inherent human notions of fairness.

Taking $P = P^+$, the utility function presented in [11] takes the following form:

$$\begin{aligned} u_p = a_p &- \frac{\alpha}{n-1} \sum_{s \neq p} \Delta a_{s,p} \\ &- \frac{\beta}{n-1} \sum_{s \neq p} \Delta a_{p,s}, \end{aligned} \tag{6}$$

where $\Delta a_{i,j} = \max(a_i - a_j, 0)$ is the positive difference between a_i and a_j. The restriction $P = P^+$, i.e. that all prosumers are consumers, will later be extended to the case that includes both consumers and producers. The utility function is similar when instead taking $P = P^-$.

The utility function (6) takes into account comparative equity; it adds two terms that compare the activity of the prosumer with the activity of all other prosumers in the network. The first term measures the utility loss from envy, i.e. others consuming more, while the second term measures the utility loss from pity, i.e. others consuming less. The parameters α and β represent the levels of envy and pity, leading to the reasonable assumptions that

$$0 \leq \alpha, \qquad 0 \leq \beta \leq 1, \qquad \beta \leq \alpha. \tag{7}$$

Since the comparative equity utility (6) explicitly considers the relation of prosumers to each other, it can simply be used with the *SW* optimization (1) to find a fair allocation. There are, however, a number of aspects unique to the congestion problem setting that demand adjustments to the comparative equity utility function as presented in (6).

Figure 2 presents a slightly modified version of the example network. The presented allocation includes inequalities among prosumers that are not clearly detrimental to its fairness. Prosumer 5 is allocated a significantly lower activity, but its activity a_5 equals its type θ_5. This means that prosumer 5 is perfectly content, and is thus unlikely to envy other prosumers. Likewise, if the other prosumers have knowledge of prosumer 5's type, it is unlikely that they will pity prosumer 5.

These situations can be taken into account by adding a factor that signifies how discontent a prosumer p is with their allocated activity a_p relative to their type θ_p. Since it is unlikely that a prosumer p will pity another prosumer for not being allocated an activity that prosumer p wanted but was not allocated itself, the discontent factor applied to the pity term should take this matter of perspective into account.

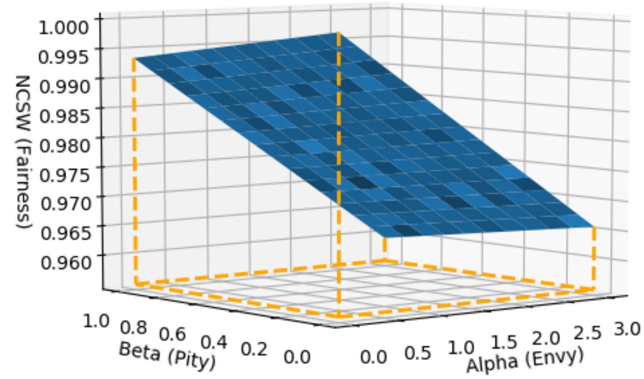

Fig. 3. *NCSW* corresponding to the allocation presented in figure 2.

The result is comparative discontent equity (*CDE*) utility:

$$\begin{aligned} u_p = a_p &- \frac{\alpha}{n-1} \sum_{s \neq p} \frac{\theta_p - a_p}{\theta_p} \cdot \Delta a_{s,p} \\ &- \frac{\beta}{n-1} \sum_{s \neq p} \frac{\min(\theta_s, a_p) - a_s}{\min(\theta_s, a_p)} \cdot \Delta a_{p,s}. \end{aligned} \tag{8}$$

If, in the situation under consideration, prosumers do not have (full) information about other prosumers' types, then the pity term should be dropped altogether.

In order to normalize the *SW* when *CDE* utility is used, instead of taking the *ASW* as suggested in Section III, the *SW* is divided by the sum of activities. This results in normalized comparative social welfare (*NCSW*):

$$\frac{\sum_P u_p}{\sum_P a_p} \tag{9}$$

Figure 3 depicts the *NCSW* corresponding to the allocation presented in figure 2 for different values of α and β, showing how prosumers' characteristics determine perceived fairness. Note that when envy and pity do not play a role, i.e. both α and β are zero, the *NCSW* takes its maximum value of 1.

NCSW is a suitable fairness measurement; normalized, independent of other qualities, and customizable through the parameters α and β. However, it applies only to groups of exclusively consumers (or producers) and does not take network topology into account.

When prosumers in the network both consume and produce, an adjustment of *NCSW* is required. Since consumers do not compete for network capacity with producers and vice versa, neither envy nor pity between the two is expected. Thus, for each consumer, the envy and pity terms in *CDE* utility should sum over only all other consumers. Similarly, the producers only compare themselves to all other producers. For a consumer, this exclusive comparative discontent equity (*ECDE*) utility takes the form

$$\begin{aligned} u_p = a_p &- \frac{\alpha}{|P^+| - 1} \sum_{s \in P^+ \setminus \{p\}} \frac{\theta_p - a_p}{\theta_p} \cdot \Delta a_{s,p} \\ &- \frac{\beta}{|P^+| - 1} \sum_{s \in P^+ \setminus \{p\}} \frac{\min(\theta_s, a_p) - a_s}{\min(\theta_s, a_p)} \cdot \Delta a_{p,s}. \end{aligned} \tag{10}$$

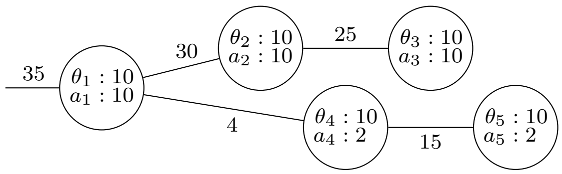

Fig. 4. The example network with only one side congested.

Besides the mode of prosumption, the network topology may also play a role in determining the set of prosumers that any prosumer compares itself to. Figure 4 presents a version of the example network that is only congested on one side. This is an interesting situation: although all prosumers have the same type and prosumers 2 and 3 on the non-congested side have been allocated more activity, a reduction of their activity cannot improve the situation for prosumers 4 and 5 on the congested side. In principle, prosumers 4 and 5 would not envy prosumers 2 and 3. This raises the question of the topological reach of comparative equity.

A possible approach to capturing this topological separation in the utility is to define regions in the network with subsets of prosumers associated to them. Prosumers from a certain subset could then have different α values depending on whether comparing to a prosumer from their own subset, or a prosumer from another subset. For example, for the network depicted in figure 4, the utility function for prosumer 4 could be

$$\begin{aligned} u_4 = a_4 \; &- \alpha \cdot \frac{\theta_4 - a_4}{\theta_4} \cdot \Delta a_{5,4} \\ &- \beta \cdot \frac{\min(\theta_5, a_4) - a_5}{\min(\theta_5, a_4)} \cdot \Delta a_{4,5} \\ &- \frac{\alpha'}{3} \sum_{s \in \{1,2,3\}} \frac{\theta_4 - a_4}{\theta_4} \cdot \Delta a_{s,4} \\ &- \frac{\beta'}{3} \sum_{s \in \{1,2,3\}} \frac{\min(\theta_s, a_4) - a_s}{\min(\theta_s, a_4)} \cdot \Delta a_{4,s}, \end{aligned} \tag{11}$$

with $\alpha > \alpha'$ and $\beta > \beta'$. This type of specific comparative discontent equity (*SCDE*) utility function that allows different α and β values when comparing to different groups is adaptable to the distribution of population and capacity constraints of the network under consideration. For instance, to distinguish groups of prosumers by region or type (e.g. hospitals).

In summary, *ECDE* utility makes a fair optimization goal with *SW* and a fairness measure with *NCSW* that both mimic notions of fairness inherent to humans. When required, *SCDE* utility may be used as a flexible way to accommodate network constraints and other attributes.

V. Congestion Management Mechanism

In this section, a congestion management mechanism is proposed in algorithmic form. Consider an acyclic network where all prosumers are consumers with simple utility (3). The mechanism allocates activities a_p to prosumers p based on the network topology and the prosumers' types θ_p. The resulting allocation A is in the solution set $\mathcal{S}$: it resolves congestion and allocated activities are bounded by prosumer types. Most real-world local energy networks can be represented by such an acyclic model.

The acyclic network is interpreted as a rooted tree with its root connected to an external network. Let T_n denote the subtree of node n and denote the line from node n directed towards the root as line n. Thus, any node n has a capacity C_n associated with it that limits the flow from the subtree T_n towards the root of the network (or, in case of the root node, towards the external network).

The allocation mechanism, presented in figure 5, takes an egalitarian approach: when congestion occurs at a line n, all consumers in the subtree T_n have the upper bound for their activities reduced to the same level. As a consequence, consumers with the lowest activity only have their activity reduced when all other consumers in the subtree T_n have their activity reduced to that same level.

Allocation Mechanism

```
1: Initialize a_p = θ_p for all p ∈ P
2: while not all nodes are marked do
3:    Select unmarked node n with no
      unmarked children and mark it
4:    if total consumption of the subtree T_n
      exceeds the capacity constraint C_n then
5:       Select value v such that ∑_{p∈T_n} min(v, a_p) = C_n
6:       Set a_p = min(v, a_p) for all p in the subtree T_n
7:    end if
8: end while
9: return A = {a_p | p ∈ P}
```

Fig. 5. The egalitarian congestion management mechanism.

Proposition 1. The set of activities a_p allocated by the allocation mechanism to the prosumers p given their types θ_p maximizes the social welfare (*SW*) on the solution set $\mathcal{S}$.

Proof. Consider a prosumer p and the final value a_p. If $a_p = \theta_p$, then the utility of prosumer p is maximal within the solution set $\mathcal{S}$ and cannot be changed to improve the *SW*.

If $a_p \neq \theta_p$, then, since all prosumers in the network are consumers, $a_p < \theta_p$. Let n be the last node where a_p was reduced. This means that the prosumer p is located in the subtree T_n for which, after executing lines 4 – 6, it holds that

$$\sum_{s \in T_n} a_s = C_n. \tag{12}$$

Since the activity a_p has not been reduced since node n and it was maximal among activities of prosumers in T_n, it follows that none of the activities of prosumers in T_n have changed since node n.

Now consider a nonempty set $V \subset P$ with $a_p < \theta_p \; \forall p \in V$ and a set $E = \{\epsilon_p \mid p \in V\}$ of corresponding activity increases with $0 < \epsilon_p \leq \theta_p - a_p \; \forall p \in V$. Let L denote the set of nodes where at least one of the prosumers $p \in V$ had their activity a_p last reduced. Since equation (12) holds for all nodes $n \in L$, the activity increases E cause congestion at all those nodes.

Let $W = P \setminus V$ and let $D = \{-\delta_s \mid s \in W\}$ be a set of corresponding activity decreases with $0 \leq \delta_s \leq a_s \; \forall s \in W$. For each $n \in L$, to resolve congestion caused by E, it must hold that $\sum_{s \in W_n} \delta_s \geq \sum_{p \in V_n} \epsilon_p$, where V_n and W_n are the subsets of V and W in T_n. If such D does not exist, then the set of activities increased by E is not in the solution set $\mathcal{S}$.

Since V is the disjoint union $\biguplus_{n \in K} V_n$ for some $K \subset L$, it follows that $\sum_{p \in V} \epsilon_p - \sum_{s \in W} \delta_s \leq 0$. Therefore, the *SW* cannot be improved by changing any number of activities. □

As demonstrated in the proof of Proposition 1, for no single prosumer p can the utility a_p be improved within the solution set $\mathcal{S}$. This entails the following corollary.

Corollary 1. The set of activities a_p allocated by the allocation mechanism to the prosumers p given their types θ_p is pareto efficient on the solution set $\mathcal{S}$.

Proposition 2. The set of activities a_p allocated by the allocation mechanism to the prosumers p given their types θ_p maximizes the Nash product (*NP*) on the solution set $\mathcal{S}$.

Proof. Taking the same approach as in the proof of Proposition 1, for each $n \in L$, it holds that $\sum_{p \in V_n} \epsilon_p - \sum_{s \in W_n} \delta_s \leq 0$.

Note that maximizing the *NP* is equivalent to maximizing $\log(NP) = \sum_{p \in P} \log(a_p)$. Adding the changes E and D gives

$$\log(NP') = \sum_{p \in V} \log(a_p + \epsilon_p) + \sum_{s \in W} \log(a_s - \delta_s), \qquad (13)$$

which, since $\log(x)$ is strictly concave, is strictly smaller than $\log(NP) + \sum_{p \in V} \frac{\epsilon_p}{a_p} - \sum_{s \in W} \frac{\delta_s}{a_s}$. For all $n \in L$, by line 6, the value v_n selected at line 5 satisfies $a_p = v_n$ for each $p \in V_n$ with activity last reduced at n, and $a_s \leq v_n$ for each $s \in W_n$. Hence, for all $n \in L$ with no descendants in L it follows that

$$\sum_{p \in V_n} \frac{\epsilon_p}{a_p} - \sum_{s \in W_n} \frac{\delta_s}{a_s} \leq \frac{1}{v_n} \left(\sum_{p \in V_n} \epsilon_p - \sum_{s \in W_n} \delta_s \right) \leq 0. \qquad (14)$$

Then since $v_m \geq v_n$ for all ascendants $m \in L$ of $n \in L$, the middle term of (14) increases when replacing v_n with v_m. Using this, (14) can then be applied to all $m \in L$. It follows that NP' (*NP* with E and D) is strictly smaller than *NP*. □

Important to any mechanism incorporating fairness is that the mechanism is truthful. This means that for the prosumers, reporting their true type is a weakly dominant strategy; i.e. prosumers cannot benefit from strategizing and misreporting.

Proposition 3. The allocation mechanism is truthful.

Proof. Consider a prosumer p and their true desired activity θ_p^*. If reporting $\theta_p = \theta_p^*$ yields a final activity $a_p < \theta_p^*$, then there is a last node n where a_p was reduced to resolve congestion. Therefore, reporting any $\theta_p > a_p$ would also cause congestion at node n and result in the same final activity a_p. Moreover, reporting any $\theta_p \leq a_p$ would result in a final activity θ_p since a_p had already been sufficiently reduced to resolve any congestion.

Therefore, reporting $\theta_p = \theta_p^*$ is a weakly dominant strategy for maximizing a_p within $\mathcal{S}$. This proves the proposition. □

Propositions 1, 2, and 3 provide a strong result concerning the allocation mechanism: given the specific problem setting, it provides a truthful and pareto efficient congestion management solution that optimizes egalitarian fairness within the constraints of the network topology.

The worst case computational complexity occurs when the mechanism must determine a value v at line 5 by sorting all k prosumers in $\mathcal{O}(k \cdot \log(k))$ time, and must do this at each of the m nodes. Hence, the worst case computational complexity is $\mathcal{O}(m \cdot k \cdot \log(k))$, where k and m are the total number of prosumers and nodes in the network, respectively.

VI. Conclusions

This paper proposed both the normalized Nash product and comparative discontent equity utilities combined with social welfare as fair optimization goals and normalized fairness measuring tools. Furthermore, this paper presented a congestion management solution in the form of an egalitarian allocation mechanism. Finally, the allocation mechanism was proven to be truthful and maximize both social welfare and the Nash product.

Future work could provide a congestion management solution based on the human-inspired concepts of fairness presented in Section IV, or extend the allocation mechanism presented in Section V to more general settings.

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