Application of Game Theory for Smart Grid Energy Harvesting and Exchange

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https://github.com/Simo39/Game-Theory-Project---Energy-Harvesting-Smart-Grid-

Abstract

In this paper, we want to analyze theoretical smart grid scenarios, with a game theoretic approach between different agents.
These are defined by prosumers. Where a prosumer may harvest energy thanks to the use of solar panels, wind turbines or other generating devices and store it in an accumulator. Prosumers therefore participate in the grid by either buying, selling energy or by being "neutral" and storing their own produced energy. The prosumers' goal is obviously to maximize their utility, which, for the purpose of this paper, is represented by monetary balance.

Introduction

In recent years the increased worldwide consumption of energy and increment of emissions has been accompanied by solutions such as the employment of generational devices capable of exploiting renewable sources of energy and the increased use of electric vehicles [1].
Electrical distribution systems have grown considerably and with their growth intelligent systems have made their way in the grid [2]. Safety and user participation are primary concerns in this grid. It is therefore necessary to give a new definition to such a system.
Smart grids can be defined as self-sufficient systems, with integration of any type and any scales of sources to the grid reducing workforce and targeting safety, reliability and quality for all consumers [3].
Advantages include reduced blackouts, reduced transmission losses and integration of devices for real-time data analysis or other Internet of Things appliances [5][10].
Consumer participation in the grid is strongly encouraged and transactions between different users are allowed and may improve the overall system and social benefit [4].
Recently a similar concept has seen its way into the Italian market.
We are speaking about Renewable Energy Communities. Users have the aim to become energy producers thanks to renewable sources and to share their production within the community [6].
The behavior of each player in the power system is understood quite well by the research community and it has been shown that interactions among players are at least as important as the individual behavior of the system [6].
Current approaches solve optimization problems in the perspective of one entity of the system, but due to the decentralization and deregulation of the market such approach is becoming less and less convenient.
Different approaches taking into account the different objectives of many players have been employed, one of which is represented by Game Theory, which studies the interaction among rational players.
In this paper, we consider a game theoretic approach to smart grid management and in particular to the monetary balance and transactions between users [8].
We simulated a smart grid consisting of a set of prosumers connected to an energy router handling transactions [11]. Each prosumer might be connected independently to the main grid [8]. The prosumer can choose to sell, buy or store their energy and therefore different strategies have been considered. We compared the outcome from the monetary point of view for each strategy, which, in turn, showed interesting results.

Literature Review

A Smart grid is a large and complex network consisting of many heterogeneous components such as households, vehicles and any device belonging to the Internet of Things [7][12]. These can be powered by either the grid or renewable sources [6][7]. Energy management in such networks requires high computational capabilities and real-time optimization.
Game theory has been shown to be an effective way to take into account the different objectives of the many players of the network [11].
To go a little further into game theory we can divide it into two branches: non-cooperative game theory and cooperative game theory. Other classifications can be made in accordance to other properties.
Most works use a non-cooperative game to model interactions among players.
In a non-cooperative game is formulated among accumulators that trade their stored energy in a double auction market, with multiple buyers and sellers [8].
A game theoretical approach is shown to perform better than a greedy algorithm when considering an utility function considering trading profits and costs.
In a Stackleberg game it is suggested to model the interactions between a power station, seen as the leader, and the prosumers, who are followers [9][13]. The paper shows the game reaches a Stackleberg equilibrium when considering the energy transactions between leader and followers [13].
In a Stackleberg game is formulated between a power company which tries to maximize its profits, and prosumers which can either buy or sell energy and try to optimize their future earnings [11]. The game shows a unique Nash equilibrium in pure strategies.
Speaking instead of Micro-grids we may have internal trading among prosumers or trading of energy between interconnected micro-grids [15].
As we work on the first approach, we see that in a game theoretic model for real time energy trading is formulated using interactions among prosumers [12]. This is modeled, as before, as a Stackelberg game with prosumers who sell being leaders and prosumers who buy energy being followers [9][14]. Pricing competition is then modeled through non-cooperative game among sellers. Similarly, another game is modeled to take into account competition between buyers when selecting the sellers.
Results show that the suggested model can effectively handle energy trading in a micro-grid and the power requested to the main grid is reduced when compared to conventional trading [16].
Finally in a model of economic incentives is suggested form market participants who cooperate in developing a micro-grid [12]. The results show the impact of micro-grid development on prices and costs for all players and using different scenarios they provided policies to prevent the micro-grids failures and to maximize the benefits of the users involved.
All these studies show how game theory can be applied to give efficacious results and improve on current implementations and optimization criteria being used.

Problem Setup

For the purpose of this paper, we consider a smart grid network consisting of a set of participants, called prosumers, capable of generating and storing energy by harvesting it from renewable sources, similar to the concept introduced in [6].
The prosumers can either exchange energy between themselves, which is handled by the router, or the main grid when they are connected.
The smart grid acts as a router, to which prosumers communicate their own demand or supply at each instance. Having a router allows to track attributes such as energy availability, energy sold by the participants, energy price and others.
We consider each time instance as independent of each other.
At each time step the participants can independently decide between three possible actions: to store, to buy or to sell energy.
Since the grid tracks transactions two different policies have been considered, first we considered a priority queue based on the quantity of energy being sold or bought, with larger orders being handled first. Then we considered a distributed energy policy, where energy bought or sold is split between other prosumers and the grid.
Concluding on prosumer, at each step each one decides the action to be taken based on its current attributes independently of each other. The grid then manages each decision based on the total demand and availability of energy, while the policy chosen gives the payout to each player.
To characterize each prosumer, we have given them a set of attributes such as (1) the amount of stored energy, which must satisfy the constraint of being within the accumulator's capacity, (2) the energy production at each time step, (3) the energy consumption at each time step and lastly (4) its monetary balance, which is obviously strictly related to the transactions made with the grid. Players equipped with an accumulator might have an amount of energy reserved for blackout events, however due to the nature of this study we have considered it to be static and therefore not needed in the framework, but such property could easily be added to expand the study further.

Framework

The problem considered in the previous section is then transposed in a game. The first step to be considered consists in the scenario where only two players are participating in the grid and their strategy set is S = {buy, sell, store}. Each player has no knowledge of attributes of the other player and has no access to the decision made by the other. Each player only has access to what's provided by the grid, such as the price of energy, and is fully aware of its own production, consumption, and stored energy for each time frame, but as said before these information is hidden to all other participants.
We start by considering a single round of the game (see Fig. 1), and then move to a repeated game with T time instances.

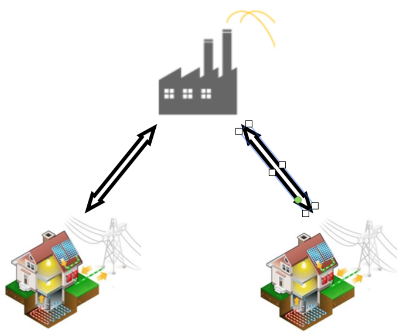


Fig. 1: 2 players game

In this case there is no knowledge about any previous decisions made by the player or any other player in the grid and the following matrix shows the situation (see Fig. 2).
After considering the case with only two players we further expand the game by considering the case where N players participate in the grid (see Fig. 3). The same rules apply to this scenario.

Even though dynamic pricing is an important factor in a smart grid to simplify the formulation we consider a fixed pricing for the energy being bought and sold. This can however simply be extended to the scenario where dynamic pricing takes place.
Now set **pe** as the unitary price for the energy. We consider the following ratios for energy exchanges.

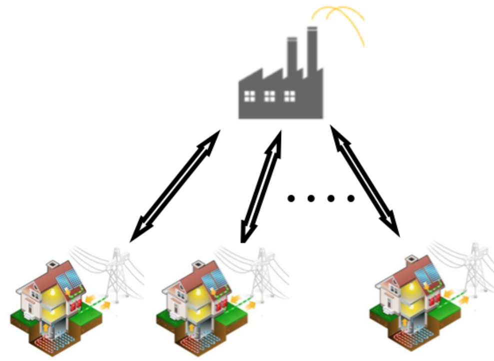


Fig. 3: N players game

Type of exchange	**Price ratio [0,1]**
Buy energy from the grid G_b	1
Buy energy from other prosumers P_b	0.75
Sell energy to the grid G_s	0.5
Sell energy to other prosumers P_s	0.75

Player 2

Player1	Buy	Sell	Store
Buy	$pe*(b_0-G_b+0.5x(b_0+G_b+P_b-100))$ $pe*(b_0-G_b+0.5x(b_0+G_b+P_b-100))$	$pe*(b_0-G_b-0.75*P_b+0.5x(b_0+G_b-100))$ $pe*(b_0+0.5*G_s+0.75*P_s)$	$pe*(b_0-G_b+0.5x(b_0+G_b-100))$ $pe*(b_0+G_{prod}+0.5x(b_0+G_{prod}-100))$
Sell	$pe*(b_0+0.5*G_s+0.75*P_s)$ $pe*(b_0-G_b-0.75*P_b+0.5x(b_0+G_b-100))$	$pe*(b_0+0.5*G_s)$ $pe*(b_0+0.5*G_s)$	$pe*(b_0+0.5*G_s)$ $pe*(b_0+G_{prod}+0.5x(b_0+G_{prod}-100))$
Store	$pe*(b_0+G_{prod}+0.5x(b_0+G_{prod}-100))$ $pe*(b_0-G_b+0.5x(b_0+G_b-100))$	$pe*(b_0+G_{prod}+0.5x(b_0+G_{prod}-100))$ $pe*(b_0+0.5*G_s)$	$pe*(b_0+G_{prod}+0.5x(b_0+G_{prod}-100))$ $pe*(b_0+G_{prod}+0.5x(b_0+G_{prod}-100))$

$$x=\begin{cases}1, & b_0+G_{prod}-100\geq 0 \vee b_0+G_b+P_c-100\geq 0 \vee b_0+G_b-100\geq 0\\ 0, & otherwise\end{cases}$$

$b_0 = initial\ amount\ of\ energy$

$G_{prod} = produced\ energy\ to\ be\ stored$

Fig. 2: 1 v 1 matrix

As said before the strategies available are to either **store**, **buy** or **sell** energy.
The strategies are always available for each player, but the following rules apply:

STORE: The player will store the generated energy in its accumulator. If the accumulator reaches its capacity the excess energy will directly be sold to the main grid and not to other prosumers. Instead, if the player decides to store energy, but its consumption exceeds the total energy available in the round he will buy the needed energy directly from the main grid.

BUY: The player will buy energy from the grid, he will decide for the amount to order, and the smart grid will handle the request by either giving energy from other prosumers, the main grid or a combination of the two. Cost will therefore be dependent on the source of energy. If a player decides to buy an amount of energy exceeding the energy expenditure plus the available storage after its own production, the excess will be sold directly to the main grid if possible. If a player instead decides to buy an amount of energy not satisfying its own demand the remaining amount required will be bought directly from the main grid if possible.

SELL: The player will sell energy to the grid, he will decide the amount being sold and the smart grid will, as before, handle the transaction. A player can sell more energy than what he has left in the storage after the daily production/consumption, however the energy being sold not already available to him will be bought directly from the main grid if possible.

The aim for each player is to maximize its profit from a monetary point of view at every round, therefore the following rules have been set.

$$\Delta_{balance}^{(i)} = pe * \left(0.75 * P_s + 0.5 * G_s - 0.75 * P_b - G_b\right)$$
$$balance^{(i+1)} = balance^{(i)} + \Delta_{balance}^{(i)}$$

Considering what has been said, P_s, G_s, P_b, G_b are set by the smart grid following the rules stated above.

For what concerns the energy balance we simply have:

$$\Delta E_{balance}^{(i)} = E_{gained}^{(i)} - E_{consumed}^{(i)}$$
$$E_{balance}^{(i+1)} = E_{balance}^{(i)} + \Delta E_{balance}^{(i)}$$

where the energy gained and consumed take into account both the energy produced and used and the energy bought and sold.
Therefore:

$$E_{gained}^{(i)} = E_{bought}^{(i)} + E_{produced}^{(i)}$$
$$E_{consumed}^{(i)} = E_{sold}^{(i)} + E_{expended}^{(i)}$$

We therefore define the following strategies:

Game Theoretic (GT) Strategy: The player will decide to play the **store** action whenever the accumulator capacity allows it. Instead, if the consumption leads to a deficit not handled by the energy balance and the production the player will play **buy** with the minimum amount required to satisfy the current round demand. Finally, if the accumulator reaches the maximum capacity in a given round the player will play **sell** with all the excess energy that could not be stored.

This strategy is defined as above thanks to the rationality of the player that wouldn't deviate from such rules as the probability of bankruptcy would be higher and the utility would be reduced due to the intrinsic penalization in buying or selling more than needed.

Always Buy Strategy: The player will play **buy** whenever possible, always satisfying the constraint given by the accumulator's capacity, and buying the maximum amount possible. In any other case we set the player to play **store**, therefore buying or selling the excess/needed energy directly from the main grid if possible.

Always Sell Strategy: The player will play **sell** whenever possible, always satisfying the constraint given by the accumulator's capacity, always selling the maximum amount possible. In any other case we set the player to play **store**, therefore buying or selling the excess/needed energy directly from the main grid if possible.

Always Store Strategy: The player will simply play **store** in any case, therefore if any excess energy is available or there is energy needed this will be bought directly from the main grid as before.

Randomized Unconstrained Strategy: The player will decide the action and the amount completely at random.

Playing these strategies could lead to bankruptcy from a monetary point of view, when such a thing happens the player is removed from the game as it cannot no longer sustain itself.

To characterize the game some parameters, have to be set for each player.

Attributes set at the start of the game	**Range for the simulation**
Accumulator Capacity	0 ÷ 100
Initial energy being stored	0 ÷ 100
Attributes set for each time instance	
Energy production	0 ÷ 150
Energy consumption	0 ÷ 150

Lastly, to control the distribution of demanded and requested energy made by the grid, three distinctive approach were coded: “split_equally”, “priority_queue” and “mixed”.
“split_equally” consists in a equal division of the supply energy among every player independently from the current energy, type of player or wallet.
“priority_queue” prioritizes higher and off-grid players requests and once these demands are satisfied, the grid manages the on-grid ones.
“mixed” combines the two approaches, firstly assuring higher and off-grid player requests and then splitting equally the remaining energy between on-grid players.

Simulations

The simulations for the games described in the previous sections were executed with a number of 1000 players and 100 rounds.
To better compare the statistics we decided to set the monetary balance and accumulator’s initial stored energy to the same value for everyone.
We considered all possible strategies in different manners. In particular we evaluated games with all players playing the GT strategy and games with mixed players, each of which had been assigned a behavior. The behavior was picked from the set: Game Theoretic, Always buy, Always sell, Always store and Randomized, uniformly at random.

To better depict the simulation some parameters were set as shown by the following table.

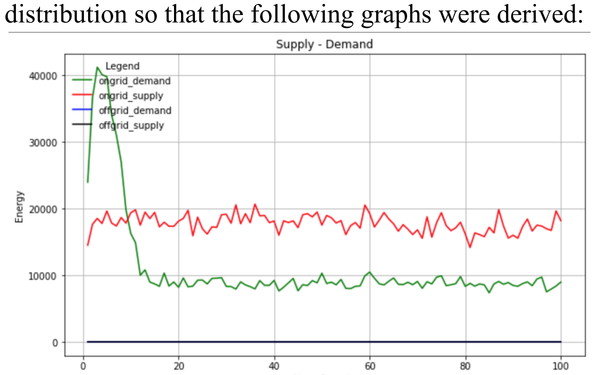
Parameters	**Value**
Accumulator’s Initial Stored Energy	50%
Initial wallet balance	500
Probability of renewable source generator for ongrid prosumers	⅓ not available ⅓ solar panels ⅓ wind turbine 0 solar panels + wind turbine
Probability of renewable source generator for offgrid prosumers	0 not available ⅖ solar panels ⅖ wind turbine ⅕ solar panels + wind turbine

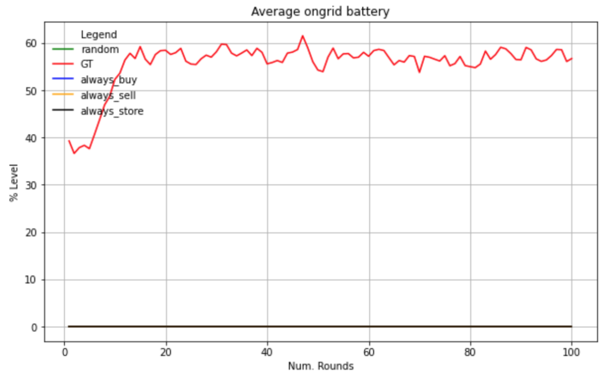
Parameters concerning each step such as energy production and consumption for each player were set randomly to mimic daily changes using a normal distribution centered around 75 units.

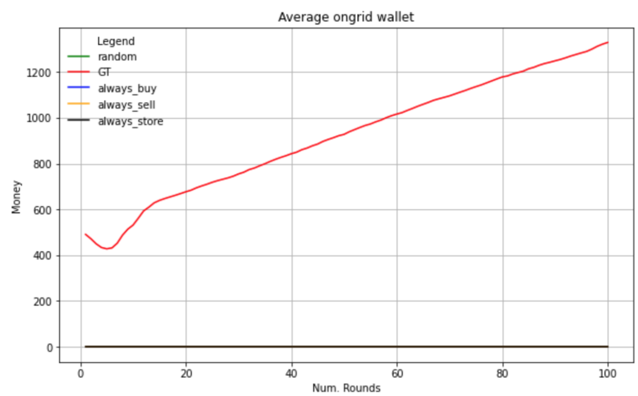
Results

For the results we started from the simple case of two players in a single round playing the GT strategy.
From a theoretical point of view the Table 1 shows the calculated utilities using the notation introduced previously.
Simulations for two players both in a single round of the game and for the repeated game have shown little to no interesting results, therefore no statistics were attached.

Moving on to the simulations with multiple players, we started from everyone being an on-grid player and playing the GT Strategy, where the grid uses the “split_equally” distribution so that the following graphs were derived:







These show the stochastic nature of the supply and demand of energy on the grid, but interestingly show how GT Strategy players that could survive all rounds were generally capable of keeping their balance or improving it while maintaining the necessary level of battery.

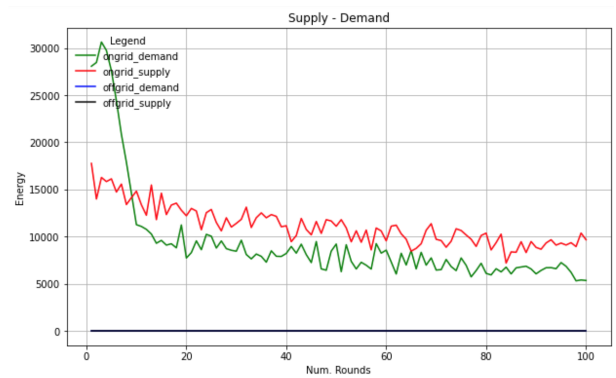
It is important to mention that due to the random nature of some values some players could not meet the necessary constraint for the entirety of the rounds and were therefore eliminated. This is shown by the following two figures:

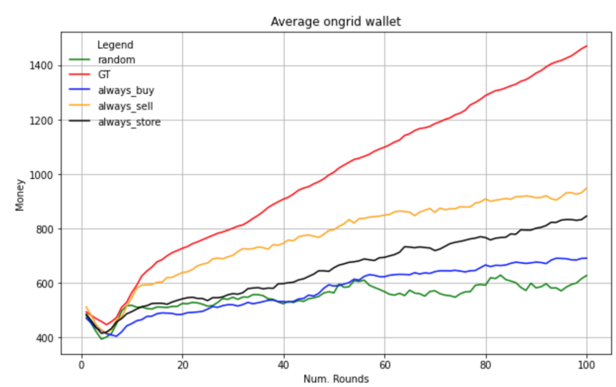
```
ROUND N.1
START OF THE ROUND
        Players in game: 1000 = ongrid[1000] + offgrid[0]
        Energy supply: 14500.31 = ongrid[14500.31] + offgrid[  0.00]
        Number of suppliers: 221 = ongrid[221] + offgrid[0]
        Energy Demand: 23953.59 = ongrid[23953.59] + offgrid[  0.00]
        Number of demanders: 377 = ongrid[377] + offgrid[0]

END OF THE ROUND
        Players in game: 1000 = ongrid[1000] + offgrid[0]
        Left Energy supply:  -0.00 = ongrid[ -0.00] + offgrid[  0.00]
        Remaning Number of suppliers: 221 = ongrid[221] + offgrid[0]
        Left Energy Demand: 9453.28 = ongrid[9453.28] + offgrid[  0.00]
        Remaning Number of demanders: 377 = ongrid[377] + offgrid[0]
        Number of excluded players in this round: 0
        Number of excluded player until now: 0
```

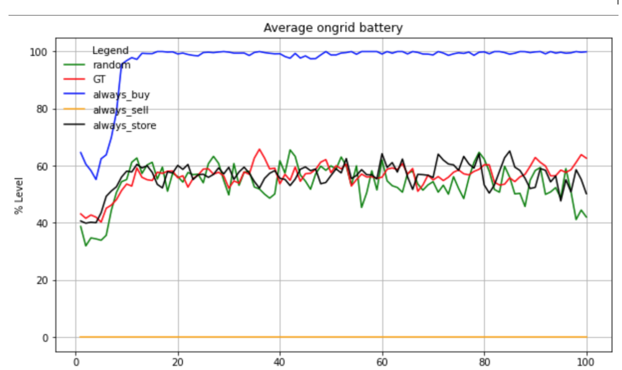
```
ROUND N.100
START OF THE ROUND
        Players in game: 594 = ongrid[594] + offgrid[0]
        Energy supply: 18179.10 = ongrid[18179.10] + offgrid[  0.00]
        Number of suppliers: 231 = ongrid[231] + offgrid[0]
        Energy Demand: 8971.69 = ongrid[8971.69] + offgrid[  0.00]
        Number of demanders: 152 = ongrid[152] + offgrid[0]

END OF THE ROUND
        Players in game: 594 = ongrid[594] + offgrid[0]
        Left Energy supply: 9207.41 = ongrid[9207.41] + offgrid[  0.00]
        Remaning Number of suppliers: 231 = ongrid[231] + offgrid[0]
        Left Energy Demand:  -0.00 = ongrid[ -0.00] + offgrid[  0.00]
        Remaning Number of demanders: 152 = ongrid[152] + offgrid[0]
        Number of excluded players in this round: 0
        Number of excluded player until now: 406
```

In fact, 406 players were eliminated, these were not included in the calculation of the statistics.

We then moved to running simulations with mixed players, assigned with different behaviors, while the other parameters were fixed as before. The following graphs were derived:







These show as before the stochastic nature of the demand and supply of the whole grid, but show interesting differences in the utility of the player.

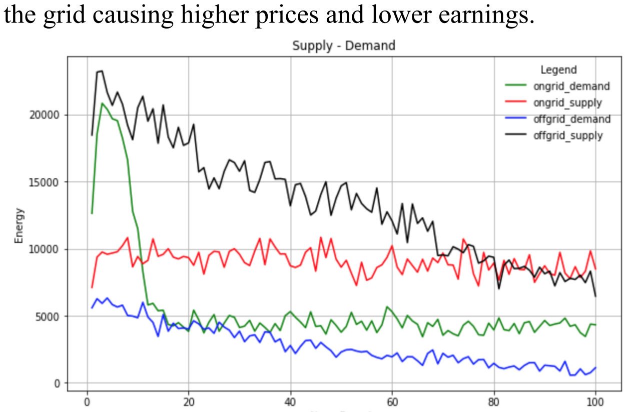
Considering their monetary balance as the utility the strategy maximizing it is the GT one. Interestingly players that were not eliminated from the game using other strategies were able to keep their balance thanks to the own production of energy and the possibility to share it. From an accumulator's level point of view as expected the players playing **Always buy** reached the maximum level of battery rapidly, while **Always sell** fall to zero after a few rounds and the others sat around the starting value set.

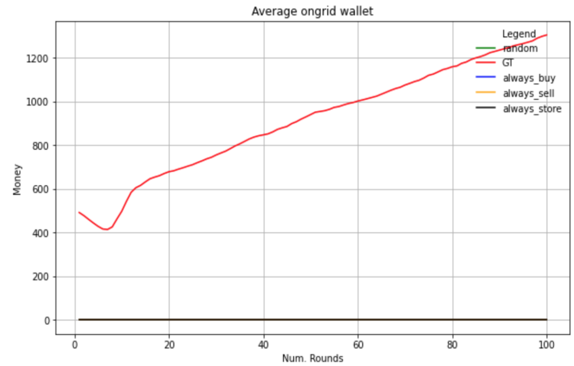
Further simulations

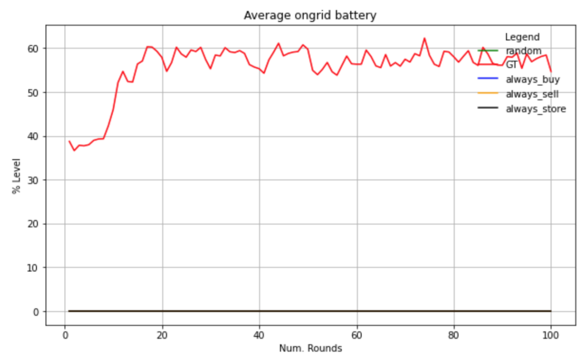
To further enhance the research done we decided to consider prosumers which do not have access to the main grid supply. Till now we had only considered on-grid users, but addition of off-grid users allows for better understanding if the behaviors depicted could work without assurance of energy supply.

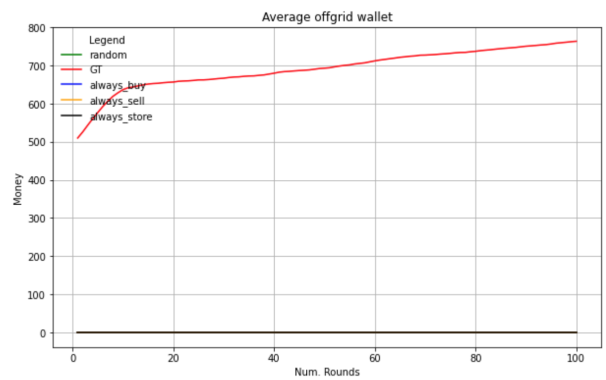
Results of the second set of simulations

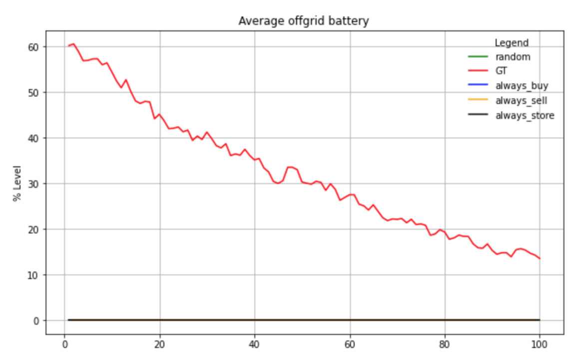
For the second set of simulation we considered mixed players (500 on.grid, 500 off-grid) using firstly just the **GT Strategy**, while the grid follows the "priority_queue" approach since the idea was to preserve the survivability of those players that are constrained to exchange energy with the grid causing higher prices and lower earnings.





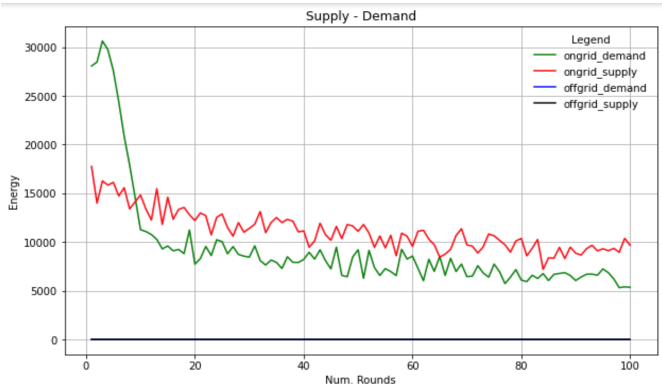


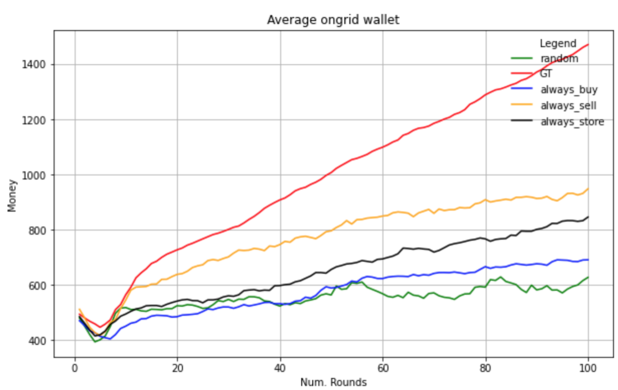


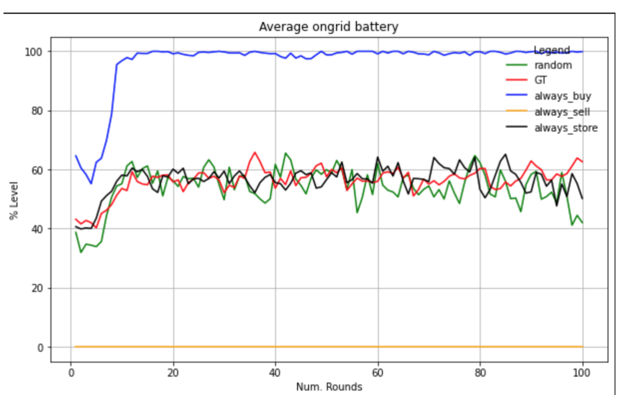


To have a complete view of the results showed above we must consider that just 295 on-grid players and 104 off-set players reached the final round. Therefore, (1) the analysis of everyone's wallet it is clear since playing **GT Strategy** allows players to increase their amount of money, (2) battery level behaviour is different between players since on-grid ones are able to stabilize it, despite random

consumption and production, while off-grid ones struggle to survive due to exchanges with the grid, (3) the decreasing number of off-grid players leads to a decreasing value of energy demanded and available to be shared.
A similar reasoning applied to on-grid players leads to think that a constant value for supply and demand associate with a drop of their number means that they are sharing more and more energy than the previous rounds.
That's what made us think to simulate with just on-grid players the following simulation but introducing all the possible strategies to verify that GT one was the best and every strategy involves the same number of actors.



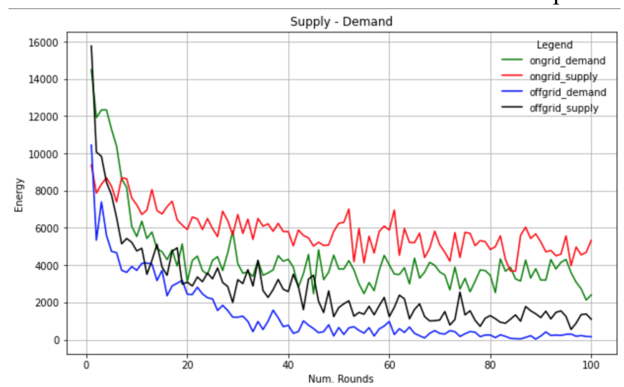


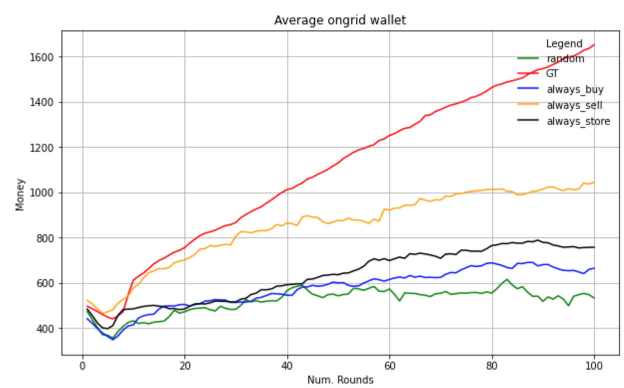


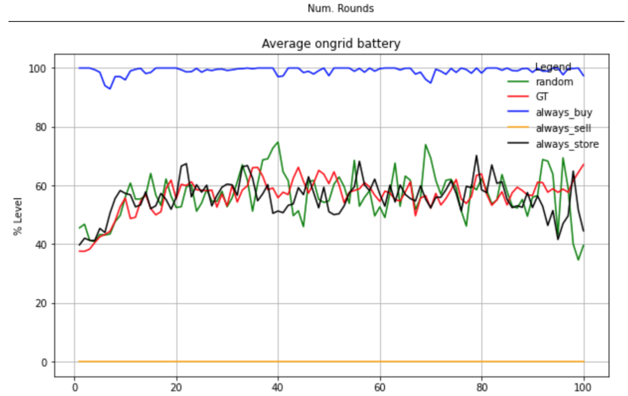
Due to the increasing value of money gained by every strategy, one may think that every one of them is worth to be played but most of the eliminated players (559) do not belongs to the GT one. Therefore, GT approach remains the best among the possible choices.

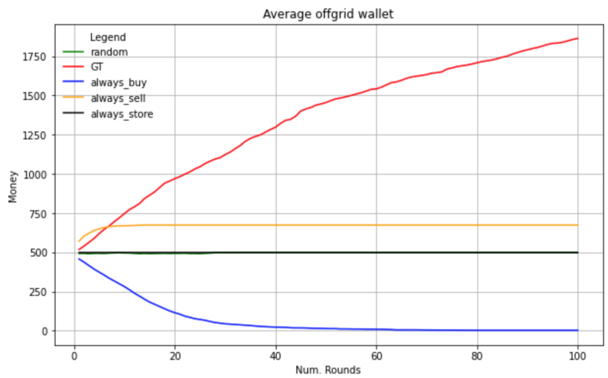
Result of the third set of simulations

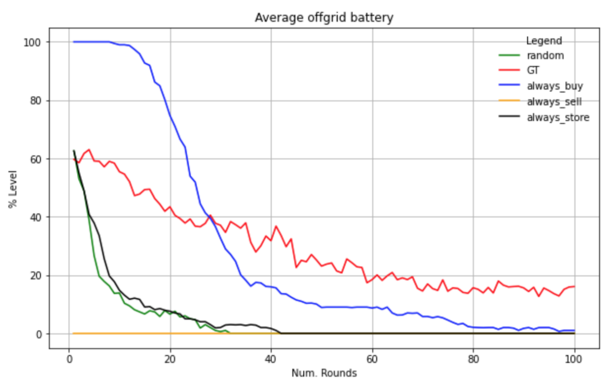
Lastly, the final simulation involved both kind of players playing all 5 strategies resulting in 100 off-grid and 100 on-grid players playing each strategy. At the same time the grid was set to play the "mixed" kind of distribution showing the following results. The expectations made on the combinations of the previous results were the off-grid players would struggle to reach the final round, while on-grid ones would be able to survive and even increase their incomes. For what concern the supply-demand ratio it was reflected from previous results that on-grid players behavior stabilizes around a constant value, while off-grid one tends to be reduced till their elimination is completed.












```
ROUND N.100
START OF THE ROUND
        Players in game: 253 = ongrid[229] + offgrid[24]
        Energy supply: 6426.85 = ongrid[5332.62] + offgrid[1094.23]
        Number of suppliers: 86 = ongrid[73] + offgrid[13]
        Energy Demand: 2562.58 = ongrid[2401.95] + offgrid[160.63]
        Number of demanders: 39 = ongrid[36] + offgrid[3]

END OF THE ROUND
        Players in game: 252 = ongrid[228] + offgrid[24]
        Left Energy supply: 2770.04 = ongrid[2770.04] + offgrid[  0.00]
        Remaning Number of suppliers: 86 = ongrid[73] + offgrid[13]
        Left Energy Demand:   0.00 = ongrid[  0.00] + offgrid[  0.00]
        Remaning Number of demanders: 39 = ongrid[36] + offgrid[3]
        Number of excluded players in this round: 1
        Number of excluded player until now: 748
```

Our expectations were confirmed: on-grid players present the same behavior as previous simulations, but it is more interesting to focus on the fact that of 500 off-set players just 24 of them survived and the large majority of them belong to the **GT Strategy** as depicted from a combined analysis of the average off-grid average battery and wallet graphs.

Conclusions

In this paper we considered a smart grid where a router, a main grid and a set of prosumers exchange energy with the grid. Applying game theory for such scenario has shown beneficial results with respect to other behaviors.

The scenario chosen for this paper was simple but could serve as basis for further research by considering dynamic pricing, real data distributions for parameter generation, more realistic benefit calculations, considering other parameters such as battery degradation, line losses, depreciation of the renewable sources generation devices and more.

However smart grid, and in particular the action done by the router could have a great impact and benefits on the overall set of users in the grid.

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