

A sustainable development of a city electrical grid via a non-contractual Demand-Side Management

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Abstract. An increasing energy consumption of large cities as well as an extreme high density of city electrical loads leads to the necessity to search for an alternative approaches to city grid development. The ongoing implementation of the energy accounting tariffs with differentiated rates depending upon the market conditions and changing in a short-term perspective, provide the possibility to use it as a financial incentive base of a Demand-Side Management (DSM). Modern hi-technology energy metering and accounting systems with a large number of functions and consumer feedback are supposed to be the good means of DSM. Existing systems of Smart Metering (SM) billing usually provide general information about consumption curve, bills and compared data, but not the advanced statistics about the correspondence of financial and electric parameters. Also, consumer feedback is usually not fully used. So, the efforts to combine the market principle, Smart Metering and a consumer feedback for an active non-contractual load control are essential. The paper presents the rating-based multi-purpose system of mathematical statistics and algorithms of DSM efficiency estimation useful for both the consumers and the energy companies. The estimation is performed by SM Data processing systems. The system is aimed for load peak shaving and load curve smoothing. It is focused primarily on a retail market support. The system contributes to the energy efficiency and a distribution process improvement by the manual management or by the automated Smart Appliances interaction.

1. Introduction

An increasing energy consumption of large cities as well as an extreme high density of city electrical loads leads to the necessity to search for an alternative approaches to city grid development. One of the promising approaches is to use the concept of Demand-Side Management to achieve load control for electrical load curve [1–4].

Nowadays the development of market mechanisms and electricity markets of the global energy sector leads to changes in rates system. Advanced metering of electricity and power by accounting tariffs with multiple rates differentiated by times of the day becomes more complicated. There is the perspective for rate changes for medium and small intervals of time. The Smart Metering concept provides for a broad implementation of modern informational and measuring components. A number of government regulations support the course [5–8].

Taking this into account, the common interests of consumers and energy companies are growing. There is a need for a program of market participants' information support and evaluation of electrical parameters, focused on differentiated by time intervals accounting, which is designed to incentive the participants and provide a non-contractual management of power consumption, distributed



generation and load of the grid components [9–12]. The introduction of these informational resources is beneficial to all the market participants:

- 1) consumers have an opportunity to assess their power consumption and manage it automatically depending upon the rates as well as to reduce their energy costs, to choose their power supplier with the most favorable terms;
- 2) owners of distributed generation can get the maximum profit from its use;
- 3) energy companies are able to influence a demand, a proposal for the distributed generation, reducing or changing the load of the grid components. Also they have an opportunity to conduct advanced statistics of consumption as well as automation of financial and contractual processes.

Existing systems of Smart Metering billing usually provide little general information about consumption curve, bills and compared data, but not the advanced statistics about the correspondence of financial and electric parameters. Also, consumer feedback is usually not fully used. So, the efforts to combine the market principle, Smart Metering and a consumer feedback are essential.

2. The dual-purpose incentives

Besides of the consumers' efforts to contribute the global idea of energy efficiency and ecology improvement, the main incentive for the consumers is an opportunity to decrease their energy costs

An analysis of the potentials to decrease the costs is aimed at the determination of rates schedule and a consumer's load curve correspondence extent. Also the analysis includes the influence of technical losses.

A case when there are M different rates (or prices of a complex rate) offered to consumer is considered. All the rates (or prices) can be ranged using their values by the principle "cheap – expensive". The most expensive rate j may be assigned to the effectiveness of $\alpha_{max} = 0\%$, the cheapest – $\alpha_{min} = 100\%$. Rates with an intermediate price c_j can be assigned to an intermediate value of α_j , proportional to the relative price difference between this value and the minimum price to the price difference of these two extreme rates.

The principle of ranking is shown in Figure 1.

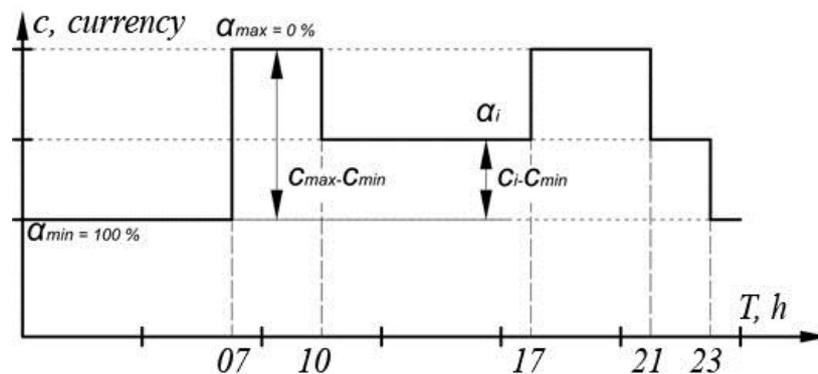


Figure 1. The rate efficiency

There are three rates: night (from 23:00 to 07:00), semi-peak (from 10:00 to 17:00 and from 21:00 to 23:00) and peak (from 07:00 to 10:00 and from 17:00 to 21:00). The basic parameter of rate j efficiency can be defined as normalized relative value obtained by minimum c_{min} and maximal c_{max} prices of night and peak rates, correspondingly:

$$\alpha_j = \frac{1 - (c_j - c_{min})}{(c_{max} - c_{min})} \cdot 100\% = \frac{(c_{max} - c_j)}{(c_{max} - c_{min})}, \quad j = 1 \dots M \quad (1)$$

Weight-average rate use efficiency index e is one of the most important parameters. It is based measured energy values W_j (or relative energy values W_{rj}) obtained by SM:

$$e = \sum_{j=1}^M \alpha_j \cdot W_{rj} = \frac{\left(\sum_{j=1}^M \alpha_j \cdot W_j \right)}{\left(\sum_{j=1}^M W_j \right)} \quad (2)$$

Thus, the coefficient of efficiency e is the weighted average of the rates. Its value represents the opportunity of savings for the consumer. There are two extreme cases:

- 1) all the electricity was consumed during rate period with $\alpha_{max} = 0\%$, which means the consumer didn't use the opportunity of savings;
- 2) all the electricity was consumed during rate period with $\alpha_{min} = 100\%$, which means the user used all rate for savings.

The actual value of the coefficient of efficiency rates is between 0% and 100%.

The weight-average rate use efficiency index e has a triple meaning:

- 1) utilized economy fact percentage;
- 2) rates schedule and a consumer's load curve correspondence extent;
- 3) the elasticity of a demand.

The consumer is able to estimate his savings and choose the most appropriate to him rate. The estimations are suitable for a-priori and a-posteriori dynamic rate selection. The energy company is able to estimate demand-side management efficiency due to the fact that rate use efficiency index is approximately equal to the elasticity of a demand.

There are another components of efficiency rating corresponding the costs for electricity transmission, power market support and other services.

Efficiency for electricity transmission costs is inversely proportional to the share of electricity consumed at the hours of the actual peak: consumption only at the hours of the actual peak leads to $\beta_{max} = 0\%$, the reduction of consumption during the hours of the actual peak is $\beta_{min} = 100\%$. The electricity consummated in the hours of the actual peak can has some corresponding intermediate value β_j

$$\beta_j = \left(1 - \frac{\sum W_j}{W}\right) \cdot 100\%, \quad j=1\dots N, \quad (3)$$

where W_j – the volumes of electricity consumption during the hours of the actual peak on working days; W_j – volumes of consumption in hours of the actual peak on working days. The rating is aimed at reducing power consumption during the hours of the actual peak.

Rating of the cost effectiveness for power transmission. Powerful consumers can be used to create a regulating effect of the load in hours of planned peak. If the maximum load exceeds the average one during the peak hours over a period of time, the efficiency of using grid power is $\gamma_{max} = 0\%$, the reduction of consumption in the hours of the planned peak is $\gamma_{min} = 100\%$. Intermediate power consumption in the hours of the planned peak can be assigned with some appropriate intermediate value γ_k :

$$\gamma_k = \begin{cases} 0\%, & W_k \geq W_{av} \\ \left(1 - \frac{W_k}{W_{av}}\right) \cdot 100\%, & k=1\dots N, \quad W_k < W_{av}, \end{cases} \quad (4)$$

where W_k is the maximum of hourly power consumptions during peak hours on working days; W_{av} is the average hourly power consumption. The rating is aimed at reducing power consumption in the hours of the planned peak.

Rating of the effectiveness of fact-to-plan consumption deviation. The feature of the retail electricity market is that consumers may not be penalized if the electricity consumption deviates at a certain time in proper directions. Therefore, it is proposed to evaluate the effectiveness of fact-to-

plan deviation in terms of the deviation of actual costs from potential costs for the case when the planning is not applied at all.

With an increase in electricity costs from the planned level to the level of potential costs with no planning, the efficiency may vary from $\delta_{max} = 0\%$, with the planned costs – $\delta_{min} = 100\%$. Intermediate volumes of consumption in the hours of the planned peak can be assigned some appropriate intermediate value δ_l :

$$\delta_l = \begin{cases} 0\%, & C_{l(p)} \geq C_{i(np)} \\ \left(1 - \frac{C_{il(p)} - C_{l(p)}}{C_{i(np)} - C_{l(p)}}\right) \cdot 100\%, & l = 1 \dots N, \quad C_{l(p)} < C_{i(np)}, \end{cases} \quad (5)$$

where $C_{l(p)}$ – costs for planned hourly volumes of consumption; $C_{i(np)}$ – potential costs for the case when the planning is not applied; $C_{il(p)}$ – costs of actual hourly volumes of consumption.

The resulting rating is formed as a weighted average for all indicators instead (2):

$$\varepsilon = \frac{\alpha C_\alpha + \beta C_\beta + \gamma C_\gamma + \delta C_\delta}{C_\alpha + C_\beta + C_\gamma + C_\delta}, \quad (6)$$

where $C_{indexed}$ corresponds to the particular type of costs listed above.

Thus, the resulting rate use efficiency index is a weighted average taking into account the share of costs for various components. Its value characterizes how much the economy has been used by the customer. The real value of the rate use efficiency will be between 0 % and 100 %.

Using the rate use efficiency index e , it is possible to determine the economy E and lost savings E_l :

$$E = \frac{\varepsilon}{100} \cdot W \cdot (c_{max} - c_{min}) \quad (7)$$

$$E_l = \left(1 - \frac{\varepsilon}{100}\right) \cdot W \cdot (c_{max} - c_{min}) \quad (8)$$

Another important parameter is the smoothing of load curve. It contributes to equipment lifetime and durability increase as well as peak lines load decrease, so it is very important. From the point of view of Math Statistics the load change can be characterized by standard variation coefficient v . But this parameter is not evident even for engineers.

One of the ideas how to estimate the variation using this parameter like an incentive for a consumer is to show him the economy based on the losses decrease. The losses in cables and wires connecting a consumer to electricity mains are considered.

From the theory of electrical power engineering it is well known that the minimum of losses during a period of time corresponds to the case when the load flows are equal at all the parts of the period.

It is useful to estimate relative reduction of the loss for single rate and the relative reduction of losses during of time period of n intervals, correspondingly:

$$r_i = \left(1 - \frac{1}{1 + v^2}\right) \cdot 100\% = \frac{v^2}{1 + v^2} \cdot 100\% \quad (9)$$

$$r = \frac{c \Delta W_{av}}{c \Delta W} = \frac{\sum_{j=1}^N W_{avj}^2 \cdot n_j \cdot v_j^2}{\sum_{j=1}^N W_{avj}^2 \cdot n_j \cdot (1 + v_j^2)} \cdot 100\% \quad (10)$$

where v – coefficient of consumption variation; ΔW_{av} – losses for the case of absolutely uniform consumption; ΔW – losses for the case of an arbitrary consumption.

Studies and the calculations show that during the day typical ν vary from 0.23 to 0.75 for different rate periods and losses decrease is from 7 % to 30 %, correspondingly. Taking into account that typical losses level is about 10 % for buildings' wiring, savings will be from 0.7 % to 3 %.

Sometimes the problem at hand is not the value of maximum power consumption itself, but the dynamics of load increase at peak times. The concept of easy load curve smoothing by means of Smart Appliances control center and Feedback center interaction is considered (Figure 2).

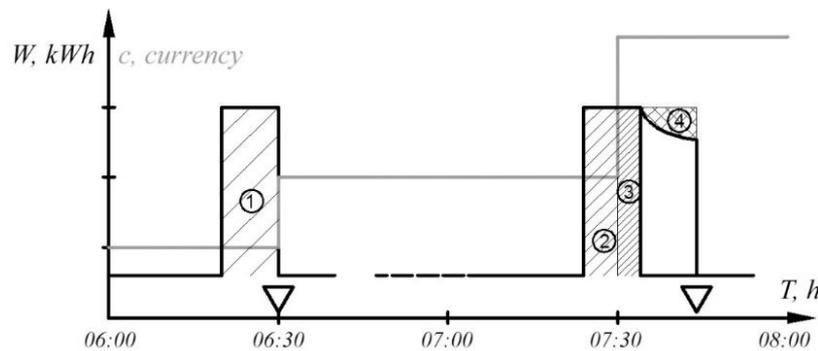


Figure 2. The planning principle

The system automatically accounts the load start-up durability which is required for the equipment, and to compare it with the time rate change time. In everyday life for consumers this turns out to be convenient – the opportunity to receive the result of the electrical installations at the time of morning rise or production process run. In the first case (Figure 2) readiness time is equal to the time rate of change. From the point of view of energy company as well as the consumer it is efficient to switch on the device so that the power consumption accounted by cheaper rate (area 1). Operation is planned in such a way that the time of a rate of change is also a readiness time of a process. When the readiness time comes later than time of rate change (the second case), it is profitable that electrical energy is accounted partially by cheaper rate (area 2) and partially by more expensive rate (area 3). The condition of profitable operation:

$$C_4 \leq C_3 - C_2 \quad (11)$$

where C_4 are the costs of equipment idle time (e.g., losses), $C_3 - C_2$ is a profit gained by the rate difference.

3. Distributed generation estimation

The particular installations of distributed generation (DG) are under consideration. Such installations are often privately owned and have small power.

First of all, the two effects of the introduction of consumers' generation cause increased attention of energy companies:

- 1) the effect of masking the load when the sudden shutdown of consumers' own generation may results in feeders overload due to the fact that they was not designed for full capacity;
- 2) the effect of the consumers' generation far exceeding the demand (e.g. during the night) can cause increased losses and undesirable reverse flows of a great value;

The RMS-imbalance of generation to the load shows the extent of balancing during M periods of time:

$$b = \left(\frac{1}{N} \sum_{i=1}^N \left(\frac{W_i - W_{gi}}{W_{gi}} \right)^2 \right)^{1/2} \cdot 100\%, \quad (12)$$

where W_i is load during a single period of time, W_{gi} is generation during a single period of time.

For the case when the imbalance value is far from zero, a permanent connection to the main grid being a damping component is necessary for the potential island of load and generation.

One-time maximum deviation of the generation from load:

$$D = \max \left(\frac{W_{gi} - W_i}{W_i} \right) \cdot 100\%, \quad (13)$$

This parameter shows the extent of instantaneous damping necessity during some particular periods of time and characterize feeders maximum load.

It is known that from the point of view of distribution utilities the benefits from the presence of DG is primarily consist of load coverage and feeders flows reduction. It results at the possibility of postponing capital investments in grid reinforcement. Maximum feeders load corresponds to the period of load curve maximum, especially at the post-failure conditions or at the repair schemes. Demand for DG and own generation of consumers in these conditions increases. That's why the dual-purpose incentives include operation time during the period of the peak rate, the share of electrical energy produced during the period of the peak rate and the income from the generation of electricity:

$$t_{\max} = \left(\frac{T_{\max} - T_{st}}{T_{\max}} \right) \cdot 100\%, \quad (14)$$

where T_{\max} is a duration of the peak rate (special or post-failure rate), T_{st} is a idle time of DG installation during the period of the peak rate.

The share of electrical energy produced during the period of the peak rate:

$$d_{\max} = \frac{\sum_{i=1}^{n_{\max}} W_{gi}}{(P_g \cdot n_{\max})} \cdot 100\%, \quad (15)$$

where n_{\max} is a number of single time periods during the peak rate, P_g is a generation power.

Using the high-price rate c_{\max} it is possible to calculate the revenue R as a product of c_{\max} and W_{gi} as well as lost revenue due to equipment idle time:

$$R_l = \left(1 - \frac{d_{\max}}{100} \right) \cdot c_{\max} \sum_{i=1}^{n_{\max}} W_{gi}, \quad (16)$$

The mentioned functions of statistics are also available using the Individual Statement.

4. The set of parameters

The entire system of the mathematical statistics including the dual-purpose incentives was established (Table 1).

All the information contained in the evaluation is both engineering and motivational (incentive) character. On the one hand, formal recommendations to the consumer are necessary as clarification of opportunities to improve the quality of consumption; on the other hand, a simple formal approach is not comprehensive. The issuance of such recommendations to be implemented with care and some of the issues of engineering psychology and marketing to be used. The recommendations to be linked with the technical, economic, operational and marketing issues facing the energy company at the moment of the recommendations issuance.

The estimation is performed by SM Data processing systems. It can be easily integrated to the Automated Meter Reading and Advanced Metering Infrastructure systems. The cores of these system are shown in Figure 3. Besides energy itself, the measured values may include active and

reactive power, currents and voltages, power quality parameters and switched on/off status, if available (for example, using IEC 61850).

Table 1. Some DSM important parameters

Parameter	Sign	Utilization	
		Energy Companies	Demand Side
Rate efficiency	$\alpha, \beta, \gamma, \delta$ [%]	Price signal	Incentives
Rates utilization coefficient	ε [%]	Demand flexibility	Economy potential
Economy	E [currency]	-	Utilized
Loss of economy	E_l [currency]	-	Missed
Average consumption	W_{av} [kW*h]	Balances, statistics	General
Consumption variation coefficient	v [%]	Statistics	-
Relative losses reduction due to load curve leveling	r [%]	Balances, statistics	Economy potential
Percentage of the load covered by DG	c_v [%]	Balances, statistics	Utilized
Generation-to-load average unbalance	b [%]	Line av. load	Missed
One-time relative generation-to-load unbalance	D [%]	Line max. load	-
Absence of idles during the high-price rate	t_{max} [%]	Offer flexibility	General
Percentage of generated electrical energy value in comparison with the max. value	d_{max} [%]	Offer flexibility	General
Profit gained by DG. during the high-price rate	R [currency]	-	Utilized
Loss of profit	R_l [currency]	-	Missed

5. Estimations performed by Smart metering data processing systems

The interaction structure is shown in Figure 3.

The system includes the unit of dynamic rate change and focused primarily on a retail market support. It contributes to the energy efficiency and a distribution process improvement by the motivation (manual management) or by the Smart Appliances interaction (automated management). The feedback of SM can be integrated with Smart Home and Smart Energy. In a manual mode feedback data are outputted to Individual Statement in easy-understandable form, in automatic mode data are used by Smart Appliance control center through WLAN/HAN. Modern systems provide for the opportunity to connect and disconnect loads during grid malfunction.

6. A software and hardware complex for an experimental study

A software and hardware complex including SM data processing system was designed and constructed. It was used for Demand-Side Management and its efficiency estimation for different buildings of Ural Federal University campus. A real efficiency of system to be proved by experience of some years practice. Nevertheless, a two of three month application enables to make some notes about non-contractual DSM efficiency.

At the beginning of experiment the following parameters were detected and calculated by the system:

- up to 37 % of customers are not aware about their electricity consumption profile;
- from 25 to 40 % of economy potential is used;

- a bit more than 0.1 % of electricity is consummated in a strict accordance with the planned load curve.
- During the experiment the following intermediate results were obtained:
- up to 34.5 % of electricity costs are reduced;
- 42.3 % electricity is consummated by the customers involved in a DSM;
- up to 5.4 % of peak load is shaved, also it is shifted at about 3 h 35 min.

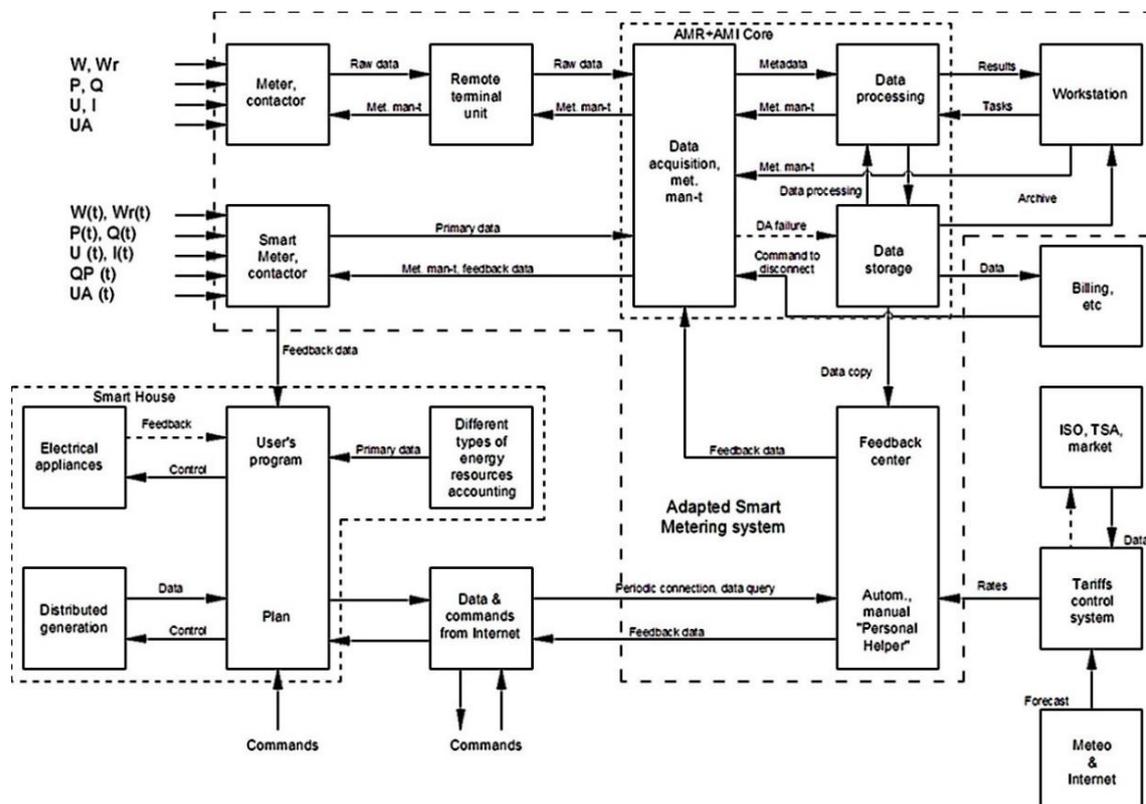


Figure 3. The structure of data processing system

7. DSM perspectives and further investigations

Although the experiment shows a number of effects listed above, the overall efficiency of DSM for city grids unload is left much to be desired. An analysis reveals a sufficient potential for the problem solution by means of the following measures.

The standard offers also include a widespread DSM units and devices use and an increasing differentiation between electricity prices during the day.

The advanced measures are mostly connected with market pricing model upgrade, but they are supposed to be effective in a case when combined with a well-grounded distribution grid structure complication. It provides an opportunity for dynamic grid reconfiguration. The measures are:

- 1) the shift of high-price zones of particular city districts or areas. It is aimed primarily at high-voltage grids unload. It requires an advanced statistics for large groups of consumers;
- 2) the shift of high-price zones of particular feeders connected to particular substations. Supposed to be efficient if a different types of electrical customers in a building connected to two or more feeders. It is aimed primarily at medium-voltage grids unload;
- 3) the use of a counter regulation by means of decreasing the load;

Also the experiment shows an appreciable load surge during 3–7 minutes of low-price zone beginning, when many consumers are switched on. To avoid this effect, a charge for the value of load ramp up is to be considered.

The listed measures are under investigations now. To incentive the consumers, a virtual prices are going to be used during the experiment study.

8. Conclusions

The paper presents the multi-purpose system of mathematical statistics and algorithms of non-contractual DSM and its efficiency estimation useful for the consumers, distributed generation and the energy companies. The estimation is performed by SM Data processing systems. The system of DSM efficiency estimation provides a number of benefits to different parties of electricity market:

- 1) consumers are motivated by financial incentives and informed by advanced analysis information about rates, economy, and schedule;
- 2) energy companies are informed about the consumers' response, they have an opportunity to smooth load curve by means of appropriate rate signals, to shave peak load decreasing grid equipment load;
- 3) the social aspect includes sufficient energy efficiency improvement;
- 4) distributed generation has an opportunity to gain the maximum profit.

The system shows its efficiency in an experiment for DSM of different Ural Federal University campus buildings. Using the experiment data analysis, the perspective ways of DSM improvement for city grid unload were obtained. They include city grid structure meshing combined with a market pricing model upgrade. The offers are under study to gather a proper statistical data.

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