NRGcoin: Virtual Currency for Trading of Renewable Energy in Smart Grids

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***Abstract*—In this paper we introduce a new decentralized digital currency, called NRGcoin. Prosumers in the smart grid trade locally produced renewable energy using NRGcoins, the value of which is determined on an open currency exchange market. Similar to Bitcoins, this currency offers numerous advantages over fiat currency, but unlike Bitcoins it is generated by injecting energy into the grid, rather than spending energy on computational power. In addition, we propose a novel trading paradigm for buying and selling green energy in the smart grid. Our mechanism achieves demand response by providing incentives to prosumers to balance their production and consumption out of their own self-interest. We study the advantages of our proposed currency over traditional money and environmental instruments, and explore its benefits for all parties in the smart grid.**

Keywords—Bitcoin, Renewable energy, Smart grids.

I. INTRODUCTION

Trading of locally produced renewable energy is addressed in literature from a market perspective where prosumers and consumers (or collectively: agents) participate in a double auction and trade energy on a day-ahead basis [1]-[3]. Buy and sell orders for energy are submitted to a public orderbook and orders are matched either in continuous time [2] or at discrete market closing times using the equilibrium price [3]. The advantages of this market-based control concept are that it achieves close to optimal allocation, neatly balances supply and demand and aligns the preferences of self-interested agents. However, bidding for energy ahead of time relies heavily on predictions of future supply or demand, the inaccuracy of which translates to higher costs for both buyers and sellers. In addition, agents need to rely on advanced trading strategies in order to maximise profit (or minimise costs) in a time-critical market. For example, prosumers unfamiliar with the market may unintentionally set a too high sell price, resulting in an unmatched order for their energy. Since there is no buyer at the time when they produce and inject the energy into the grid, prosumers make zero profit, unless they invest in batteries that can store the untraded energy, instead of feeding it to the grid. Those agents can then inject the energy at the time they find a buyer. Although batteries can increase the profits of prosumers under such a market model, their major limitation in the smart grid is that they mask agents' true consumption and production profiles from the utility provider [4].

Market-based energy trade reduces the dependency of agents on the Utility Provider (UP), as energy supply and demand is matched directly between individual agents, resulting in a more decentralized and competitive environment. However, locally produced energy nowadays covers only a small percentage of all consumption and therefore the UP still needs to supply a large portion of the energy to cover the total demand. Thus, considering the role of the UP in a trading mechanism facilitates the implementation of that mechanism on top of the current infrastructure and state of affairs and allows for faster transition to a smart grid setting.

In this paper we propose a new virtual currency, called NRGcoin, as a novel contribution to the energy trading paradigm in smart grids. Instead of relying on a time-critical energy market or additional battery storage, our mechanism converts locally produced renewable energy directly to NRGcoins, independent of their value on the market. The currency can then be exchanged at any time on an open market for its monetary equivalent, e.g. Euro, Dollar, Pound, etc. In our model, producers do not rely on batteries, but continuously feed energy into the grid. Payment is received in the form of NRGcoins based on *actual* usage, rather than predicted, as consumption is measured and billed in near real-time. In contrast to previously proposed energy markets, this model is much closer to the current operation of the grid, allowing for smooth deployment and adoption of the proposed method.

In our mechanism information of local energy production and consumption is sent from smart meters of agents to the street-level low voltage energy substations of the Distribute System Operator (DSO) at 15-minute intervals. This information is then used to determine the rates at which prosumers are rewarded for their produced energy and consumers are billed for their withdrawn energy. These rates also motivate agents to balance supply and demand, as well as lower production and consumption peaks. For example, during times of low demand or high production, the cost of energy is low, and analogously, low supply or high demand drive the prices up. Every 15 minutes each street-level substation independently determines the rates for energy consumption and for production for all dwellings in that neighbourhood. In this way, our mechanism maintains the important role that the DSO currently plays in the energy market. Although in some countries the billing is performed by the utility provider, rather than the

DSO, for ease of exposition in this paper we assume the latter is responsible for both the energy delivery and the billing.

In Section II we outline the details of our mechanism and in Section III we elaborate on the properties of the proposed currency. In Section IV we summarize our approach and propose directions for future work.

II. RENEWABLE ENERGY TRADE

Locally produced energy is fed into the grid and payment is received in the form of NRGcoins. Analogously, agents pay NRGcoins to the DSO for their energy usage. On the one hand, the DSO collects and distributes these payments using variable consumption and production rates in order to motivate agents to match energy supply and demand. On the other hand, new NRGcoins are generated in the system to prevent the currency from being deflationary. In Figure 1 we present a schematic setup that will help visualise the complete cycle of energy and currency exchange in our mechanism for each 15-minute period (called time slot). Note that since substations are only informed of the injected energy and not the produced energy, henceforth by produced energy we mean energy injected in the grid. Similarly, energy consumption is the energy delivered to the household from the power line, excluding the consumption of the own produced energy.

A given prosumer $\boldsymbol{P}$ generates certain amount of renewable energy and feeds x of it to the grid, simultaneously broadcasting this information to all nodes in the NRGcoin network. These nodes then update the public record of $\boldsymbol{P}$ with $f(x)$ NRGcoins, as defined by the decentralised NRGcoin protocol. Thus, function $f(x)$ is responsible for generating the NRGcoins which then enter circulation. In addition, the local substation $\boldsymbol{S}$ to which $\boldsymbol{P}$ is connected to has measured the total local energy production t_p and total local consumption t_c in that slot. That substation then publicly transfers $g(x, t_p, t_c)$ NRGcoins from the balance of the DSO to that prosumer, where $g(\cdot)$ is the production price function defined by the DSO. Thus, for injected energy x prosumer $\boldsymbol{P}$ obtains NRGcoins from both the NRGcoin protocol (to ensure new money enters the system) and the local substation (to motivate agents to match consumption with production). Note that the amount of received currency only depends on functions f and g (where $f \ll g$) and is not linked to the monetary value of NRGcoins on the market. This is to ensure that energy injection and the earnings from it are not tightly coupled, as the energy market may be unfavourable at the time of injection. The energy is simply converted to NRGcoins, which can then be traded at a later time for potentially higher profit. This mechanism increases prosumer's revenue without the need for investing in energy storage, although the latter can further increase the profits from generated energy.

At any chosen time slot, $\boldsymbol{P}$ joins an exchange market with an order to sell m of her NRGcoins in exchange for Euro. Similarly, a given consumer $\boldsymbol{C}$ decides to buy n NRGcoins with Euro and places a buy order in the market. If according to the market regulations these two bids are matched, the seller $\boldsymbol{P}$ releases $n \leq m$ NRGcoins to the buyer and receives her asked Euro from the market, while the buyer $\boldsymbol{C}$ releases the offered Euro amount to the seller and receives his n NRGcoins. He then pays $h(y, t_p, t_c)$ NRGcoins for his energy consumption of y to local substation $\boldsymbol{S}$. Note that $\boldsymbol{P}$ and $\boldsymbol{C}$ need not belong to the same substation, as NRGcoins can be traded across neighbourhoods, or even countries. In analogy to the price function for production $g(\cdot)$, the price function for consumption $h(\cdot)$ is defined by the DSO.

Below we elaborate on the first component of our mechanism – the trading of energy using NRGcoins (left part of Figure 1) as well as balancing supply and demand. In Section III we describe the process of generating NRGcoins and exchanging the latter for fiat currency (right half of the figure) as well as what the benefits of the new currency are.

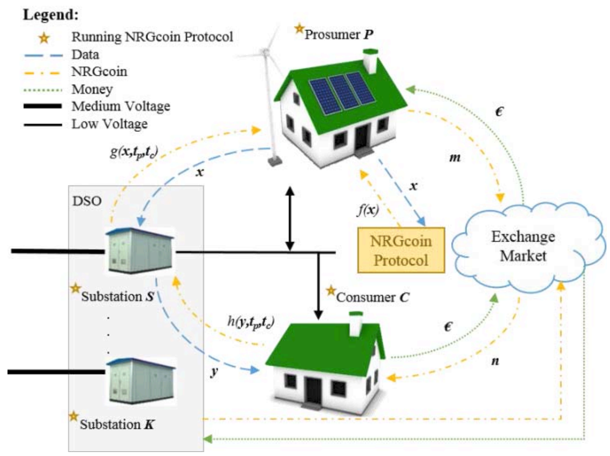

Fig. 1. Schematic setup

A. Buying and Selling Energy

Each prosumer may use her produced energy to cover her own demand first. The excess energy is then fed into the grid. Information of local energy production and consumption is sent from smart meters of prosumers to the street-level low voltage energy substations of the DSO at 15-minute intervals. This information then helps determine the new rates for energy consumption and production. One way to motivate prosumers to feed in just enough energy to cover demand is to shape the production price function as a bell curve. Too little or too much production is valued low, while the highest rate is when energy supply matches demand. So we define $g(\cdot)$ as:

$$g\left(x, t_p, t_c\right) = \frac{x \cdot q}{e^{\frac{\left(t_p - t_c\right)^2}{a}}} \tag{1}$$

where q is the maximum rate at which producers are rewarded for their input energy x when total supply t_p matches total demand t_c and it is defined by the DSO; and a is a scaling factor for the case where $t_p \neq t_c$. When total energy production completely covers total consumption, the function is at its peak and simplifies to $g = x \cdot q$. On the other hand, when $t_p \gg t_c$ or $t_p \ll t_c$, producers are paid at a rate of $g \to 0$ NRGcoins. Thus, function g serves the purpose of variable feed-in tariff that motivates producers to match demand, as producing too little or too much energy results in lower revenue for those agents. The price function $h(\cdot)$, according to which consumers pay for their withdrawn energy y, should be designed to motivate consumers to shift their demand to periods of high production. Energy consumption is cheap during times of overproduction and expensive otherwise. One possibility for $h(\cdot)$ is:

$$h\left(y,t_p,t_c\right)=\frac{y\cdot r\cdot t_c}{t_c+t_p} \quad (2)$$

where r is the maximum cost of energy delivered by the DSO when the energy supply by prosumers is low. When production matches consumption, on the other hand, the substation charges consumers with $\frac{r}{t_c}$ per kWh. Lastly, when $t_c \ll t_p$ then $h \to 0$ and thus the cost of consumed energy during overproduction is close to 0, motivating consumers to shift their energy usage to periods of overproduction.

B. Balancing Supply and Demand

Price functions g and h are designed to align the objectives of agents. Since the rates at which substations pay prosumers depend on local supply and demand, different prosumers may earn different number of NRGcoins for the same amount of injected energy at different locations of the smart grid. Again, these rates are independent from the current market value of the NRGcoins.

The difference in the rates is related to the balance of local energy production and consumption that the DSO strives to achieve, as well as for flattening supply and demand peaks. For example, the value of generated energy in a neighbourhood full of producers will be much lower than the NRGcoins that a single producer will earn in a neighbourhood full of consumers. Thus, the value difference imposed by the DSO may stimulate consumers to install renewable energy generators and become producers, while at the same time discourage excess production or consumption that overload the transmission lines. Similarly, consumers are motivated to shift their consumption away from demand peaks and towards production peaks, as that will lower their energy bill.

The more energy supply matches demand, the more NRGcoins producers receive from the substation and the fewer coins are paid by consumers to the substation, as the additional energy it needs to supply to that neighbourhood is low. In this way agents strive to balance supply and demand, i.e. achieve demand response, out of their own self-interest. Prosumers are motivated to feed just enough renewable energy to the grid, while consumers minimize their costs by shifting their consumption pattern towards time slots of higher production. Note that the parameters q and r of price functions (1) and (2) need to be carefully configured to ensure that the profit of the DSO is always positive and covers the costs of energy transmission.

Since locally produced energy nowadays covers only a small percentage of consumption within neighbourhoods, the DSO still needs to distribute electricity produced by power stations, to cover the total demand. As the incentive mechanisms of NRGcoin (functions *f*, g and h) will likely alter typical supply and demand profiles, reliable forecasting techniques are needed to improve the energy supply planning of the DSO and decrease its costs.

III. NRGcoin

As explain above, NRGcoins are rewarded by local substations for energy injected into the grid. Note that the DSO does not *issue* the currency, but simply collects and distributes payments, based on the consumption and production price functions. In addition to those paid by the DSO, new NRGcoins are generated into the system by the decentralized NRGcoin protocol and awarded to producers. These additional incentives further stimulate energy production and at the same time prevent the currency from being deflationary. The currency is generated by producing renewable energy, as opposed to any other digital currency that is generated by computing power and hence energy expenditure. The value of NRGcoins is determined solely by trading the currency on an open exchange market – higher demand for NRGcoins increases their monetary value, while a large number of sells drives their value down.

A. Generating and Exchanging NRGcoins

The rate $f(x)$ at which NRGcoins are generated depends only on the amount x of renewable energy fed into the grid. This amount is broadcast[1] by the smart meter of the producer to all other smart meters running the NRGcoin protocol, allowing all participants in the NRGcoin network to keep track of the earnings of each smart meter and their transactions. Note that although transaction information is associated with smart meters, the latter are not publicly linked to actual prosumers and therefore all earnings and transactions are anonymous as far as agents are concerned. The process of generating NRGcoins draws parallels to the process of mining in the Bitcoin protocol and similarly, the bookkeeping of earnings and transactions resembles the Bitcoin blockchain [5]. NRGcoins are generated according to function $f(\cdot)$ defined as:

$$f\left(x\right)=b\cdot x \quad (3)$$

where b is a constant specifying the rate at which NRGcoins are rewarded to prosumers for their injected energy x and is defined by the NRGcoin protocol, running on all smart meters.

To procure or sell NRGcoins agents participate in an online currency exchange market. An agent who needs NRGcoins (e.g. in order to pay for his energy consumption) can place a buy bid on the market, and analogously, an agent with excess amount of NRGcoins can submit a sell bid. Each buy bid contains the requested amount of currency and the price at which the agent is willing to buy. In addition, the bid contains order configurations [6], such as whether the agent prefers partial or full match of her bid, and whether the bid needs to be discarded if not matched immediately, or can stay in the orderbook and possibly be matched at a later time. For ease of exposition, in the remainder of this section we assume that all bids can be matched partially and remain in the orderbook if not matched immediately. When a buy bid is submitted to the market, all sell orders with a price lower than the buy price are matched (lowest sell orders first) until the buy quantity is fulfilled. Any remaining unmatched buy quantity is added to the orderbook. All sell bids are processed in analogous fashion, starting with

[1] It is assumed here that security mechanisms are in place to prevent tampering with the smart meter.

the highest buys first. Thus, orders are matched only if the buy price is higher than or equal to the sell price. The buyer pays the price he has specified in his bid and the seller – her specified sell price. The owner of the market earns profit from the difference between matched buy and sell bids, as well as a possible commission fee to keep the market running.

The smart meters of agents can employ learning techniques that automatically determine the optimal quantity of NRGcoins to trade in the market and an acceptable bidding price. The learning mechanism selects a bid quantity that aims to minimize the amount of excess currency, i.e. the difference between the current amount of NRGcoins the prosumer owns and the amount it is expected to need in the future. In addition, the bid price is determined by observing the inside-market, i.e. the difference between the lowest outstanding sell and the highest outstanding buy in the orderbook, and taking into account the risk preference of the prosumer. For example, placing a very high selling price bears a high return, but also a high risk, meaning that the probability of finding an appropriate match with a consumer agent is low. Thus, learning mechanisms aim to maximize the revenue of the agent, considering its preferences.

Bidding strategies for trading agents have been a hot research topic for the last decade. For example, the Power Trading Agent Competition (TAC)[2] [7] is a yearly competition simulating future retail electric power markets. The agents in the market act as retail brokers in a local dwelling, purchasing power from a retail market as well as from local sources, such as homes and businesses with solar panels, and selling power to local customers and into the wholesale market. Retail brokers use learning mechanisms for their bidding strategies in order to make profit, while balancing supply and demand [8]. As the environment involves a highly dynamic setting with competitive agents, adaptive algorithms that learn by observation [9] have proven to be very successful at this competition.

The difference between our approach and Power TAC is that the latter involves self-interested brokers who aim to learn profitable electricity *tariffs* in order to attract more customers. The brokers compete against each other and attempt to contract consumers, prosumers and electric vehicle customers by offering competitive subscription rates. In our mechanism, agents do not subscribe to energy brokers, but to the DSO, via which the energy is traded.

B. *Properties of NRGcoin*

NRGcoins offer a number of advantages over traditional money, other digital currencies, and environmental instruments currently in place, as we outline below.

1) NRGcoins and Fiat Currencies: According to our mechanism, locally produced renewable energy is continuously "converted" to NRGcoins. Their advantage over fiat currency is that they serve as the right to receive an equivalent quantity of energy in the future independent of NRGcoin market value. For example, a producer who injects 10 kWh in one day will receive a corresponding NRGcoin amount, based on the total supply and demand measured at the substation. She then can use this amount at any time (e.g. after two years) to pay for 10 kWh of consumption from the grid, irrelevant of NRGcoin market value, but given equivalent energy supply and demand conditions as during injection. Therefore, what this new currency brings for agents is security towards increasing energy prices. The currency can be spent either to buy equivalent amount of renewable energy at a later point in time, or traded for fiat money on a market, whichever is more profitable for the agent. In this way NRGcoins act as a form of efficient and infinite battery for agents, without masking their consumption and production patterns from the DSO, or simply as a business of buying and selling the currency for profit. In general, it gives individual agents accessible means to not only support renewable energy generation, but also invest in the energy market as a whole – something that is not trivial in the current state of affairs. The DSO, on the other hand, benefits from using NRGcoins as a "debt instrument" with high liquidity, allowing it to quickly convert this currency to cash. Paying prosumers with NRGcoins instead of fiat currencies is a form of energy debt that the DSO has to those prosumers. Delivering energy rather than money to cover its debt enables the DSO to focus a larger portion of its cash assets on investments, instead of relying on bank credits and paying their associated interest rates.

It should be noted that the NRGcoin currency is an added value to the energy trade mechanism and not designed to be an indivisible part of it. The trading of energy is also possible using fiat currency instead of NRGcoins by modifying price functions g and h to consider the value of the fiat currency, and dropping function f. Thus, in an initial phase the energy exchange mechanism can be implemented with little change to the current operation of the grid, and therefore simplify deployment. Then, in a second phase, our digital currency can replace fiat money in order to provide all benefits listed in this section. Nevertheless, detailed investigations need to be carried out to determine to what extend standard currency can be used in the deployment phase of our approach.

2) NRGcoins and Environmental Instruments: The new "green currency" also resembles tradable green certificates (TGCs) [10], [11] (or renewable energy certificates, depending on country) as a measure of produced renewable energy and as a way to support clean energy efforts. However, a drawback of both instruments is that neither of them can serve as a proof that fossil fuel has been offset, but only that renewable energy has been generated. Carbon credits (CCs), on the other hand, serve to reward greenhouse gas reductions, or penalize emissions above certain quota.

While 1 CC is equivalent to preventing 1 tonne of CO_2 (or equivalent greenhouse gases) from entering the atmosphere, it is not trivial to quantify the reductions from generation of green energy. As a result, CCs are less suitable to serve as an exchange unit for trading renewable energy. In contrast, 1 TGC is the equivalent of 1MWh of renewable energy produced (or injected in the grid, depending on definitions, which vary). NRGcoin is designed to have a much finer granularity than TGCs and thus enable the quick exchange of small or even fractional amounts of energy. Moreover, unlike TGCs, NRGcoins can be traded across countries and can serve as an international currency for green energy. The exact quantifica-

[2] http://www.powertac.org/

tion of the currency's granularity is related to function *f*, the definition of which is a product of ongoing work. Nevertheless, the properties of the introduced currency remain decoupled from its quantification.

It should be noted that with TGCs consumers purchase the environmental benefits of renewable energy, but not the energy itself. Therefore, consumers need to buy the energy in addition to the certificates they purchase. While NRGcoins are simply a form of payment for that energy, TGCs supply additional information regarding the time, place and method of energy generation, and serve to track energy from its point of origin to its final point of use. Thus, it is possible to use both in combination – buy energy using NRGcoins and separately purchase TGCs to prove green energy consumption.

Some other differences with existing environmental instruments are that both CCs and TGCs are issued by a certain body, which imposes purchase obligation to some consumers, and need to be retired upon use. In contrast, NRGcoin is decentralized and has no issuer. They remain in the system and can be re-sold, as their purpose is not to prove consumption, but to pay for it.

3) NRGcoins and Digital Currencies: Similarly to other decentralized digital currencies, such as Bitcoin [5], NRGcoin is not regulated by any bank or central authority and it is not tied to the stock market or fiat currencies. However, unlike Bitcoins, which are generated by sheer computing power and hence energy expenditure (in a process called "mining"), NRGcoins are generated by injecting locally produced renewable energy to the grid. Although NRGcoin is not regulated, it is dependent on its community. Therefore its trade value can have large fluctuations as a result of market speculations.

A concept similar to NRGcoin is presented in [12], where the authors propose the use of "energy tokens" for trading of energy. However, their currency is issued by the utility provider for the main purpose of anonymising energy trade.

IV. SUMMARY AND OUTLOOK

In summary, instead of relying on a day-ahead energy market to sell or purchase their energy, prosumers simply inject to or draw from the grid, as is the current state of affairs, but at prices that depend on measured supply and demand of energy. Payment is in the form of NRGcoins, the value of which is determined based on trades in an open currency exchange market. Using concepts from the increasingly popular Bitcoin phenomenon, our novel mechanism creates a microeconomic ecosystem that allows prosumers to trade locally produced renewable energy at competitive prices. At the same time agents are incentivized to balance energy supply and demand out of their own self-interest and thus flatten production and consumption peaks. Lastly, our proposed approach is scalable – newly joining agents do not increase the complexity of the energy trade thanks to the local substations, or of the currency exchange, as the NRGcoin protocol is decentralized.

As this concept is still work-in-progress, extensive simulations need to be carried out, backed up by microeconomic theories, to determine the parameters of the price functions of the DSO and the rate at which NRGcoins are generated in the network. Once these parameters are set, our approach will be compared against state-of-the-art market mechanisms to determine the benefits of the proposed approach in terms of prosumer earnings and overall fairness of the system. Last but not least, special attention needs to be paid to the privacy and security aspects of the NRGcoin protocol and in the design of the smart meter middleware.

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