A smart contract oriented whole system regulatory model for electricity networks – A working paper

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Abstract: Redesign of energy system governance processes will become necessary, owing to technological and societal change. The emergence of both smart metering systems and smart contract platforms provides opportunities for system regulators to re-define roles and responsibilities. In particular, self–enforcing programmatic incentive structures can be created and implemented. This paper presents a smart contract oriented general architectural model for public electricity networks. It defines the monopoly roles within the system and a framework for instantiation of economic games between metered participants. An example incentive system that creates a whole system Schelling point around demand-generation balance is presented. A number of potential benefits of the proposed regulatory model and incentive system, over existing regulatory structures, are described – they include a lower barrier of entry for balancing participation, improved prediction, increased resilience to cascading voltage collapse, and reduced regulatory complexity.

1. Introduction

Redesign of energy system governance processes will become necessary, owing to technological and societal change. The factors underlying this change can be categorised as digitisation, decentralisation, democratisation and decarbonisation [1]. Addressing the resulting regulatory challenges in a piecemeal way risks additional cost and system insecurity [2]. Hence there is a need for a whole system architectural model, spanning physical and informational domains, that helps system designers conceptualise, and account for, the changes. Sandys et al [3] recommend that a renewal of electricity system regulatory structure be oriented, firstly, around its users.

From the perspective of the users of electricity networks, five things are paid for: energy (imported or exported over a given time window), power (the maximum rating of the connection for the given time window), security of supply (the continued existence of supply voltage at the metered terminals), safety (e.g. sufficient fault level to operate protection, but not too much) and self/outward signalling of values (e.g. sustainable, expense minimising, indifferent) – as personal values are a component of energy purchasing decisions [4, 5]. Unless a metered user can source all of these things independently, then the existence of an external supply, the grid, is required. Two things, within a user's influence, lead to a lower cost external supply; certainty of future usage and compromise on service quality (e.g. curtailment of power at peak times). Under present systems the end-user is not easily able to access cost savings from contribution to cost reduction in these categories. This leads to the question of how the system might be redefined to facilitate no-barrier optional access to these cost-savings – one way is through game theory [6, 7].

An electricity system can be viewed as a game between metered users with rules defining how incentives and penalties reach users. The rules require defined roles and responsibilities across the system. Technological changes bring the possibility of automating many of the rules, and, crucially, their enforcement. These changes are typified by smart metering and smart contracts.

Smart contracts represent trustworthy programmable money. Using them, value can be automatically transferred between parties as a result of some digital event (e.g. a reading from a smart meter). They are a tool to instantiate rules for economic games. This gives system architects the opportunity to design incentive systems that help electricity system efficacy and stability. One consideration in this regard is the concept of Schelling points.

Schelling points refer to when consensus of outcome is achieved without any direct communication between the participating parties. In electricity systems, the desired implicit consensus, Schelling point, should be a balanced system. To bring this about, two innovations could be introduced; a requirement of metered users to predict their future usage and the modification of a meter's rewards in relation to the quality of its predictions. However, such a system must also address practical requirements for spare generation (and potentially load) capacity.

Helm [8] argues that the provision of spare generation capacity is best achieved through transparent auctions with discretionary constraints (e.g. volume and price) set by a responsible body. Helm shows that this approach has been successful in the capacity auctions in Great Britain (GB) and recommends that the approach be taken further. Smart contracts are means to instantiate transparent auctions. The general approach could reasonably be applied to:

- Energy
- Balancing commitments
- Black-start commitments
- Network operation and maintenance duties
- System operation duties
- Auction constraint setting duties

The question of when such auctions should take place follows. In consideration of this, one might define a general version of a 'gate' in relation to a particular usage period. In present systems 'gate closure' is typically the moment at which bilateral energy trading stops and system operator managed short term balancing takes over. More generally, however, a ‘gate’ can be considered a formal moment occurring before the time of use for a given settlement period. If taken this way, a series of ‘gates’ can be thought of as extending back in time from the time of use. The first gate might represent the capacity auctions, years ahead, and the final gate 30 minutes (or perhaps 15 in future) ahead may include a balancing commitment auction. Certain gates could be selected for auctions related to governance, network operation, maintenance, and planning roles.

The roles and responsibilities related to planning, operation and maintenance of public electricity networks have been under focus recently, in part due to the increasing decentralisation of generation [9]. One proposal, in Great Britain (GB), is a transition from Distribution Network Operator (DNO) to Distribution System Operator (DSO); where distribution operators are given more responsibility for the stability of their networks [10–12]. Another proposal, by Helm [8], recommends publicly owned separate Regional System Operators (RSO) that set auction constraints together with separate maintenance and operation roles. Importantly, any new regulatory framework must seek to constrain the risk of unforeseen complex control interactions that may result from the distribution of stability responsibilities [13].

Wright [14] suggests that the DSO might end up as a market facilitator with balancing responsibility. Relatedly, peer to peer energy trading has received attention [15–17]. However it is challenging to achieve consistent energy costs across a society under peer-to-peer schemes, if the negotiations take place in a local context. It has been argued that alternatives, centralised negotiation based schemes, would create an infeasible burden on existing dispatch and settlement procedures [18, 19]. Limits in the scalability of peer-to-peer trading schemes have also been identified [20]. Despite this, emerging communication techniques [21] and solutions to smart contract platform scaling constraints [22] make it likely that this becomes a less significant limitation. If the data collection, communications and economic enforcement are abstracted away, using the smart metering system combined with smart contracts, regulators will be left with a choice of rulesets defining the economic game between metered participants.

Sandys et al [3] recommend that a regulatory principle of “aggressive transparency” be applied to areas with natural monopolies, such as DNOs. Underlying this, however, is a challenge to achieve transparent processes without exposing private metered usages. The field of cryptography, including the topic of zero-knowledge proofs [23] (where possession of information can be proven without exposing it), holds potential solutions in this area [24, 25]. Furthermore, there is potential for privacy preserving schemes to be incorporated into smart contract rules [26, 27].

Cyber-security in energy systems is critical. Security considerations range from the vulnerability of hardware and data acquisition systems [28], to vulnerability of those with operational responsibility [29], to the vulnerability of the game-theoretic rules that describe the whole system [30, 31]. When viewed from a regulatory level, two contrasting approaches become apparent. The first, following Kerckhoff’s principle [32], defined by Shannon as “the enemy knows the system” [33], contrasts with a “security through obscurity” or “security through complexity” approach. The growth of distributed Kerckhoff systems, embodied by public permissionless blockchains, e.g. bitcoin [34], is well documented [35] – these are typically reliant on the safe handling of private keys by system participants. In any case, but especially if an electricity system simplifies and unifies its rules using smart contracts, the “security through obscurity” approach becomes less viable.

In this paper, a new smart contract oriented whole system regulatory model is defined. Following its definition, an example incentive system ruleset is described and demonstrated with a simple case study. The presented model has the following characteristics:

- Whole system, sequential-timeframe, multi-gate transparent negotiations.
- A system governor role that sets negotiation constraints.
- Network operator roles delineated by voltage level and Normally Open Points (NOPs).
- Metered connections between distinct network segments.
- A requirement that network operators must maintain network operation following loss (for a period of time set by the system governor) of any combination of metered connections.
- All meters are compelled to submit predictions.
- All meters have a reputation factor for use in an incentive system.
- The incentive system rewards prediction accuracy and timeliness as well as helpful contributions to system balancing.
- Rewards accumulate per network segment in relation to prediction quality.

2. Whole System Regulatory Model

The proposed regulatory model for public electricity networks is divided into 4 layers; physical, data, rules and governance. A number of monopoly roles are defined, as shown in Table 1. The physical layer consists of the physical network connecting metered users as well as the meters themselves. The data layer is the securely stored data indexed by meter identification numbers. The rules layer consists of rules which act on the data layer’s data, including economic transactions – it is here that payments made to and from each

Table 1 Monopoly roles

Layer	Role	Description
Governance	System Governor	Setting constraints for negotiations and roles.
	Rule Maker	Definition of economic rules for negotiation and settlement.
Rules	Rule Operator	Instantiation of economic rules for negotiation and settlement.
Data	Data Operator	Storage of and interface with meter and economic data.
Physical	Network Operator	Operation of energy networks.
	Meter Operator	Operation of the metering system.

metered user are calculated and enforced. The governance layer is where the roles and rules are defined.

2.1. Governance Layer

The "rule maker" and "system governor" roles are at the governance layer. The "system governor" role has responsibility for the setting negotiation constraints after analysis of the system's practical need (e.g. spare capacity requirements). The "rule maker" role includes the discovery and definition of the rules for the system's economic game. This allows for transparent competition in the discovery of the rules. One way of achieving this is through algorithm discovery competitions, such as the SHA-3 cryptographic hashing competition [36].

2.2. Rules Layer

In the rules layer, the rules, and constraining parameters, of the system's economic game are set and automatically enforced (i.e. with smart contracts). The rules are separated into transparent negotiations (e.g. auctions) and settlement stages with respect to a given time of use. The rules contain an incentive system for the metered participants. The sequence of negotiation and settlement procedures operate across sequential time windows with multiple gates. These time windows are synchronised with a system pulse, set, for example, at 30 minutes. Likewise, the gates are conceptualised as existing at every system pulse for a given time-window. The gates are used as a reference point for negotiations with respect to a time of use. This includes negotiations for energy use, balancing commitments and monopoly duties. The process of negotiation at gates for sequential time windows, followed by settlement, is illustrated in Figure 1.

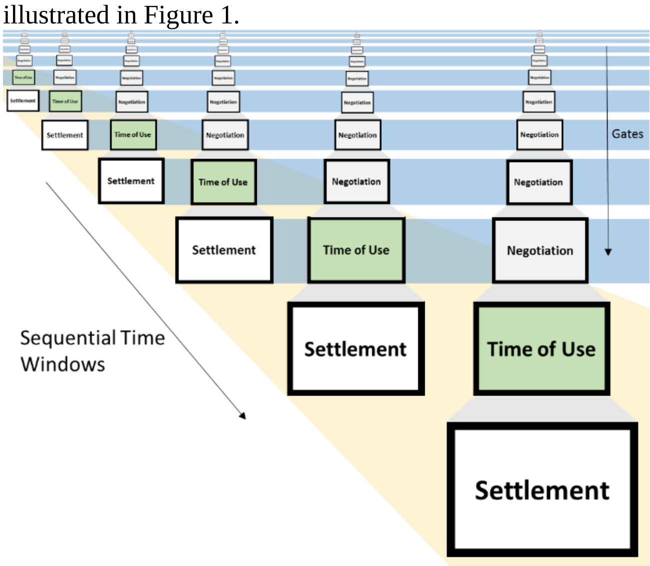

Fig. 1. *Multi-gate negotiation at sequential time-windows*

2.3. Data Layer

The data layer integrates the payment system, the metering system (physical layer) and the game-theoretic rules (rules layer). The data in the data layer, indexed by meter identification number, includes; the meter user's deposit, the actual metered usages for each time window, predictions for usage in future time windows and a Prediction Performance Factor (PPF) - a reputation value between 0 and 1 for usage in incentive schemes within the rules layer.

2.4. Physical Layer

The physical layer is the metering system and the physical electricity network. The network operation roles are delineated by open points and voltage level in the physical network. The interfaces between network operators are metered. These meters represent the network operator in the data layer and rules layer. A subset of the system's meters are presumed to be capable of frequency response verification, as described in prior work [37] – this is to allow participation in negotiations for balancing commitments. To address system security, a duty to ensure that each network should remain operational for a pre-defined period (specified by the system governor) upon the loss of any combination of metered connections (including those to higher voltage levels) is specified. The whole system model and the example incentive system ruleset are illustrated in Figure 2.

3. Example Incentive System Ruleset

The example ruleset creates a whole system Schelling point around system balancing. It does this by rewarding deviations from predictions that turn out to be helpful. For instance, if the whole system generates less than expected, then those meters that generate more than they predicted (or have lower demand) will be rewarded in proportion to the mis-prediction (with modification by its PPF reputation). Conversely, if the meter generates less than predicted, or has higher demand, then it must pay a penalty. The meters are thus categorised as helpful or unhelpful, for each time window. The amount paid by unhelpful meters is set by the cost of whole system balancing commitments, for that window. As the cost of balancing commitment usage was offset by the helpful meters, the rewards of the helpful meters are paid by the unhelpful meters. The principle is shown in Figure 3.

Where prediction rewards are unclaimed (due to a PPF of <1), the unclaimed amounts accumulate in accounts associated with the meter's network operator area. These amounts are public and can be used as an investment signal – e.g. a high amount accrued to a particular network operator area indicates that the connected meters tend not to predict well and that it would therefore be profitable to connect, say, a battery with a well predicted output. Conversely, an area with little or no accumulated rewards implies that the constituent meters are generally good at predicting, therefore the value in connection of a well predicted battery is relatively lower for that network.

The meters are categorised either as price takers or price makers (synonymous with 'critical' and 'non-critical' in previous work [38]). With respect to energy import or export in a given future time window, price takers accept the price per unit output from a series of transparent negotiation procedures participated in by the price makers. The process is replicated for balancing commitments. In Figure 2, separate sections of the data and rules layers are dedicated to the price making meters participating in the negotiations.

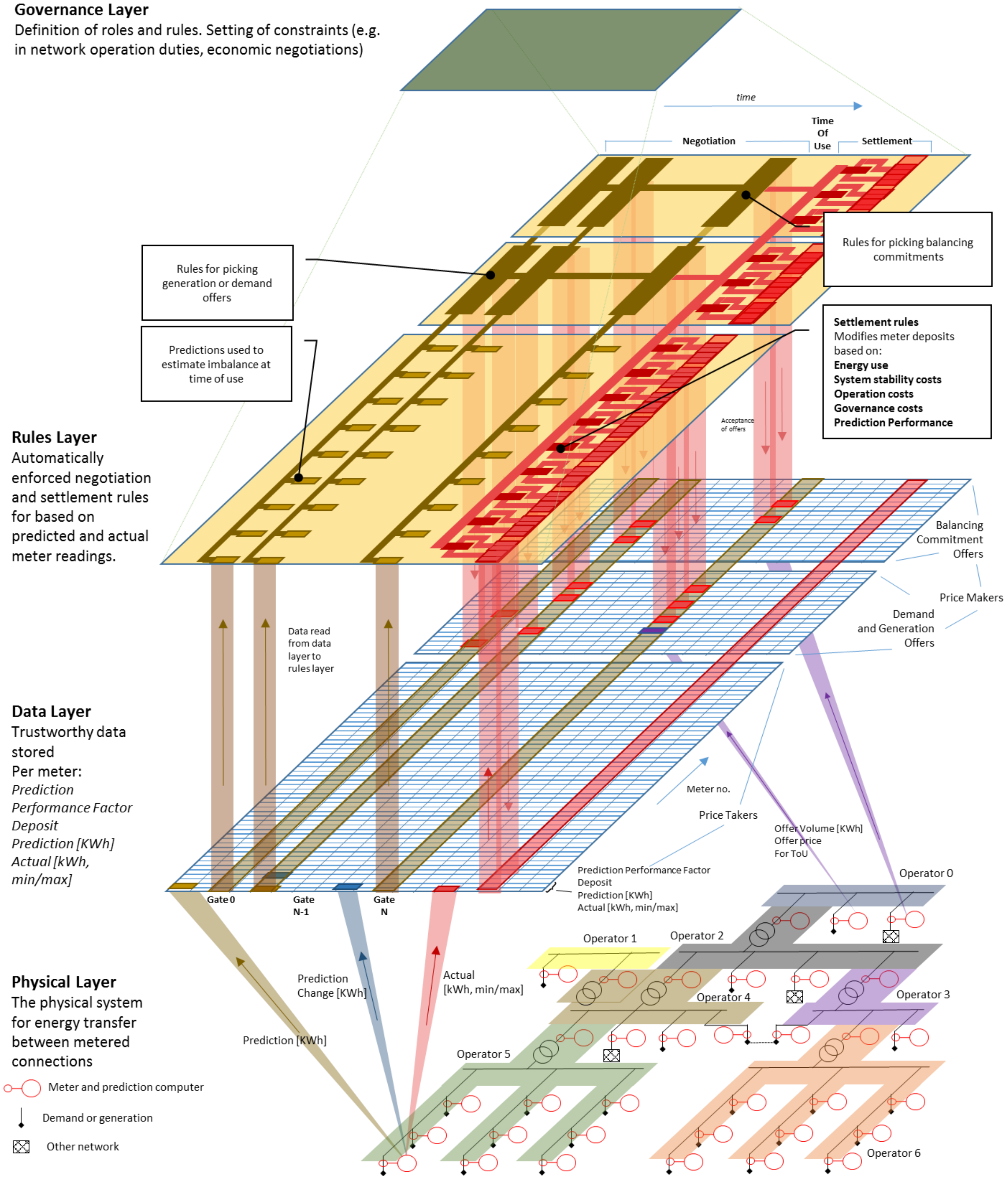

Fig. 2. *Overview of the architectural model*

The example ruleset follows the multi-gate negotiation, time of use and settlement structure – as introduced in Figure 1. At the negotiation gates, price makers submit offers and price takers have associated predictions. The predictions are processed and a subset of the offers are accepted. At the time of use, the meter system records actual usage. At settlement, payments are enacted based on actual usage. Helpful/unhelpful contributions to system balancing are rewarded/penalised, modulated by meter reputation (PPF). Meter reputations are updated based on prediction accuracy, timeliness and consistency. Unclaimed rewards accrue to network areas. Each network operator is assigned one or more meter and the meters are arranged in a system meter graph describing the meter interconnections.

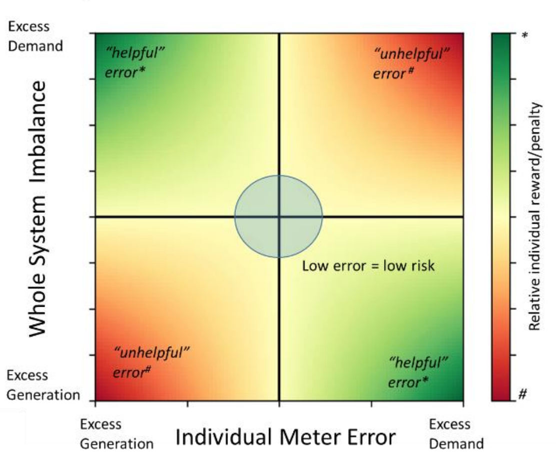

Fig. 3. *Principle of the incentive scheme*

3.1. System Meter Graph

The network operator licence areas are arranged into set of S meter groups, $\boldsymbol{G} = \{g_0, g_1, g_2 \dots, g_s\}$ where each group is a mutually exclusive subset of the N meters, $\boldsymbol{M} = \{m_0, m_1, m_2 \dots, m_{\boldsymbol{N}}\} \in \mathbb{Z}$, in the system. Each network operator has at least one meter connected to a higher voltage level. Where there is no higher voltage level, a virtual meter is added to account for the losses. The meter groups are defined as a directed graph (multitree), $\mathcal{D} = (\boldsymbol{G}, \mathcal{A})$, where $\mathcal{A}$ represents the arcs from meters to groups. An example system meter graph is shown in Figure 4 – this relates to the network topography shown in Figure 2. A number of convenience functions are defined to refer to specific meters or groups of meters; these are shown in Figure 4 and defined below:

$PARENTSOF(m)$ Function returning the parent group(s) of meter m's group in $\mathcal{D}$, returns $\emptyset$ if the group has no parent group, or if the meter has no group (virtual meters).
$GROUPOF(m)$ Function returning the group of which meter m is a member, returns $\emptyset$ if the meter has no group (virtual meters).
$CHILDRENOF(m)$ Function returning the meters of the child group in $\mathcal{D}$, of meter m. Returns $\emptyset$ if the meter has no child group.
$ROOTGROUPS = \{m : PARENTSOF(m) = \emptyset\}$ The set of meters that have no parent groups.

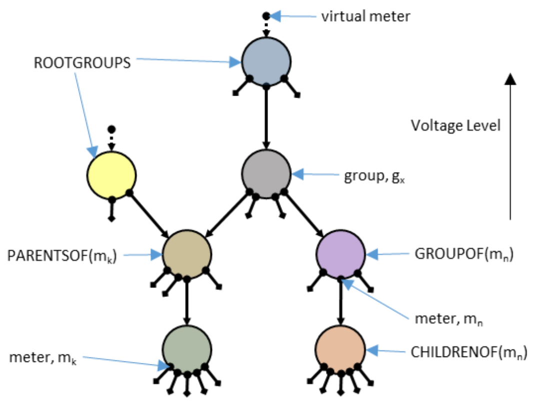

Fig. 4. *Example System Meter Graph*

3.2. Sequential time windows and gates

The framework operates around a set of sequential time windows, $\boldsymbol{T} = \{t_0, t_1, t_2 \dots, t_\infty\}$, and, for each time window, a set of L gates extending back in time, $\boldsymbol{F} = \{f_0, f_1, f_2 \dots, f_L\}$.

3.3. Before Time of Use – Energy Price Calculation

Before time of use, the whole system imbalance is calculated:

$$PredictedImbalance_{t,f} = \sum_{m:m \in ROOTGROUPS} p_{m,t,f} \quad (1)$$

where $p_{m,t,f}$ is the predicted usage of meter m for time window t at gate f.

Following this, energy offers are picked until the imbalance reaches a threshold, set by the system governor. Similarly, balancing commitment offers are selected up to a threshold, again set by the system governor. The process is repeated across the set of gates $\boldsymbol{F}$. Therefore the predicted imbalance will tend to reduce as the gates get closer to the time of use, as the accepted offers are accounted for. Additional offers are accepted based on changes in the predictions of price takers or at the discretion of the system governor. The algorithms are shown in the appendices.

At the final gate the energy price, $EnergyPrice_t$, is known – it is the mean per unit energy price agreed across all of the gates. Similarly, the balancing commitment costs are known.

3.4. After Time of Use – Settlement

An overview of the settlement procedure is shown in Figure 5, with references to the equations. After the time of use, the actual usage of each meter is known and the error in prediction can be calculated, for the individual meter:

$$PredError_{m,t} = a_{m,t} - p_{m,t} \quad (2)$$

where $p_{m,t}$ is the prediction and $a_{m,t}$ is the actual usage for meter m at time window t, they are negative for generation and positive for demand.

A function is defined that returns *true* if an individual meter's prediction error turned out to help correct the whole system imbalance in a given time window and *false* if it contributed to the imbalance:

$$ISHELPFUL_t(m) = \begin{cases} true, & \dfrac{PredError_{m,t}}{TotBalVol_t} > 0 \\ false, & otherwise \end{cases} \quad (3)$$

where $TotBalVol_t$ is the total balancing volume used in Wh for time window t. For consistency, it is negative for generation and positive for demand.

The prediction performance factor $PPF_{m,t}$ for each meter is calculated using a function that returns a value between 0 and 1. This is used to modify a meter's reward based on its prediction accuracy, consistency, helpfulness of errors, and variance across the time frame. It is not explicitly defined here, but takes the form shown in Equation (4), where $a_{m,t,min}, a_{m,t,max}$ are the minimum and maximum instantaneous values seen over time window t, $t_{pred,t}$ is the time before t that the latest prediction was made, $p_{m,t,min}, p_{m,t,max}$ are the minimum and maximum of all the meter's predictions made for time window *t*.

The PPF is used to produce a reward modifier, $RMod_{m,t}$, it is only applied if the meter made a helpful contribution to system balancing:

$$RMod_{m,t} = \begin{cases} PPF_{m,t}, & ISHELPFUL_t(m) = true \\ 0, & otherwise \end{cases} \tag{5}$$

A meter's penalty is calculated based on its proportional contribution to whole system imbalance, see Equation (6), where $TotBalCost_t$ is the total cost of balancing (for commitments and actual usage) for time window *t*.

The individual penalties are combined to give the total penalties paid within a group, g:

$$Penalty_{g,t} = \sum_{m:m\in g} Penalty_{m,t} \tag{7}$$

These group penalties are collected and paid to the helpful price taker meters within the group. The rewards are modified by the PPF, and unclaimed rewards (if PPF is <1) accumulate linked to the group's network area in a variable named $AUR_{g,t}$- the "Accumulated Unclaimed Reward" for group g at time window *t*. The reward for each meter is calculated thus:

$$Reward_{m,t} = \left(\frac{Penalty_{GROUPOF(m),t} + AUR_{GROUPOF(m),t}}{N_{g,t}}\right) \times RMod_{m,t} \tag{8}$$

where $N_{g,t}$ is the number of meters in group g, and $AUR_{g,t}$ is the Accumulated Unclaimed Reward for the meter's group g at time t calculated at the previous timestep, see Equation (9).

$$AUR_{g,t} = Penalty_{g,t-1} + AUR_{g,t-1} - \sum_{m\in g} Reward_{m,t-1} \tag{9}$$

where $AUR_{g,t-1}$ is the Accumulated Unclaimed Reward for group g at time window *t-1* (previous time window).

The energy payment for each meter is the actual energy usage multiplied by the negotiated energy price, where the usage of any child groups is subtracted. The payment calculation is dependent on whether the meter has a child group – meters that do have child groups are network operators. This means that network operator meters have to pay for the losses on their network, see Equation (10).

Finally, the total payment from (or to) each meter is calculated by:

$$TotalPayment_{m,t} = EnergyPayment_{m,t} + GovOpPayment_{m,t} + Penalty_{m,t} + Legacy_{m,t} + BalCost_{m,t} - Reward_{m,t} \tag{11}$$

Where $GovOpPayment_{m,t}$ is the governance and operation cost of the system attributed evenly to time windows and meters, $Legacy_{m,t}$ is the payment (or reward) due to any legacy subsidy schemes for a particular meter, $BalCost_{m,t}$ is the cost of balancing commitments and verified balancing actions.

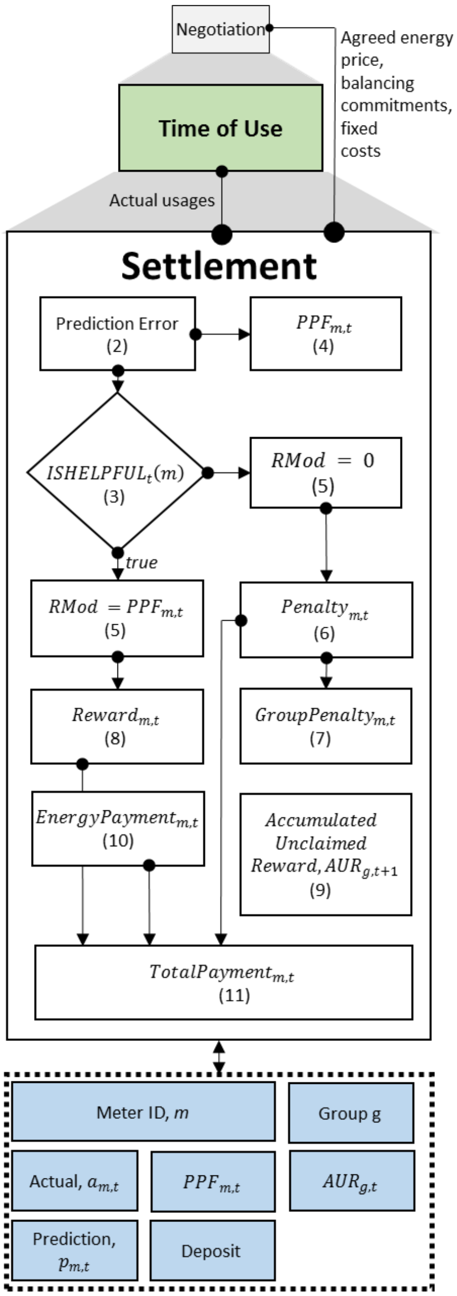

Fig. 5. Overview of the settlement ruleset

$$PPF_{m,t} = ppf\left(a_{m,t}, p_{m,t}, t_{pred,t}, p_{m,t,min}, p_{m,t,max}, a_{m,t,min}, a_{m,tmax}, PPF_{m,t-1}\right) \quad (4)$$

$$Penalty_{m,t} = \begin{cases} 0, & ISHELPFUL_t(m) = true \\ \dfrac{PredError_{m,t} \times TotBalCost_t}{TotBalVol_t}, & otherwise \end{cases} \quad (6)$$

$$EnergyPayment_{m,t} = \begin{cases} EnergyPrice_{\ t} \times a_{m,t}, & CHILDRENOF(m) = \emptyset \\ \left(1 - \dfrac{\sum_{ch \in CHILDRENOF(m)} a_{ch,t}}{\sum_{cu \in PARENTSOF(CHILDRENOF(m))} a_{cu,t}}\right) \times EnergyPrice_{\ t} \times a_{m,t}, & otherwise \end{cases} \quad (10)$$

3.5. Case study – settlement incentive scheme

The operation of the example ruleset is demonstrated using the simple system shown in Figure 6 and the data in Table 2. Figure 6 shows the simple system's line diagram and the associated meter graph. The shading on the line diagram indicates the delineation of network operator responsibility. The first meter, meter 0, is a virtual meter to account for the energy losses of Operator 0.

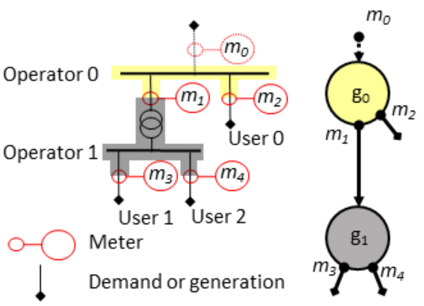

Fig. 6. - Case study example

Table 2 shows example predicted usages, actual usages, balancing commitments, balancing volumes, balancing payments, prediction performance factors (PPF) and fixed costs for each of the meters. The remaining columns show the application of the presented settlement ruleset – the associated equation number is shown in brackets in the column headers. The initial Accumulated Unclaimed Rewards are set to 0. A notional negotiated energy price of £10/MWh is used in the calculations. All units are notional as the case is illustrative.

In the example, meters 3 and 4 mis-predict their usages and meter 2's balancing commitment is called upon to compensate. Meter 3 mis-predicts in a way that reduces the balancing compensation required from meter 2, and so is rewarded at the same rate as meter 2. As meter 3's PPF is less than 1, there is an unclaimed reward. Meter 4 mis-predicts in a way that means meter 2's balancing commitment is needed – therefore it pays a penalty relating to the cost of balancing – some of this goes to meter 3, some accumulates as unclaimed reward. Meters 0 and 1 are the network operators. The network operator's pay for their losses and for unhelpful mis-predictions, as can be seen by the outcome for Operator 1. They are also rewarded for helpful mis-predictions. The most profitable network operators, therefore, are those that are best able to predict the whole system need and adjust their networks to suit, as well as minimising losses (assuming no generation excess).

Table 2 Case study example - incentive scheme

Meter Id, *m*	User Id.	Group, *g*	Balancing Commitment [MWh]	Predicted usage [MWh]	Actual Usage [MWh]	Error (2) [MWh]	Balancing Volume [MWh]	Balancing Payment [£]
0	Operator 0	Ø	0	1	1	0	0	2.5
1	Operator 1	1	0	10	11	1	0	2.5
2	User 0	1	-4	-11	-12	-1	-1	-10
3	User 1	2	0	5	4	-1	0	2.5
4	User 2	2	0	4	6	2	0	2.5

Meter Id, *m*	PPF	ISHELPFUL (3)	Penalty (6) [£]	Reward (8) [£]	$AUR_{g,t+1}$ (9) [£]	Energy Payment (10) [£]	Fixed Costs [£]	Total Payment (11) [£]
0	0.9	False	0	0	0	10	20	32.5
1	0.8	False	10	0	10	10	20	42.5
2	0.9	True	0	0		-120	20	-110.0
3	0.5	True	0	-5.0	15	40	20	57.5
4	0.5	False	20	0		60	20	102.5

4. Implications

The proposed whole system regulatory model and example incentive system ruleset have a number of potentially advantageous characteristics, when set against traditional approaches:

Clarity of investment signals for infrastructure upgrade and energy storage device connection. This is achieved in a number ways:

- the accumulating unclaimed rewards linked to network topology.
- the increased granularity of network operation licences.
- a prediction performance factor linked to meter numbers – this can used by planners, along with other data, to analyse where infrastructure upgrades will be required in future.

Participation optionality in system balancing - there is no necessary additional attention or activity requirement placed on users of the electricity network, but those that wish to participate in system balancing have negligible barrier to entry, from a regulatory perspective.

Timely, consistent and accurate prediction incentive - the example incentive system for a well-predicted system permeates through to all participants. This is in contrast to present day regulatory frameworks, where such signals are only clearly available to a subset of participants.

Transparency in price derivation due to use of transparent negotiations with discretionary constraints.

Systemic cost of intermittency/inflexibility is borne by originators Metered users are automatically rewarded or penalised according to their contribution to system balancing. When applied to intermittent sources, such as wind and solar, it ensures that the systemic cost of intermittency is borne by its originators. When applied to inflexible sources, such as nuclear, it ensures that the systemic cost of inflexibility is borne by its originators.

Optional tax and subsidisation of meter subsets - the proposed system makes the subsidisation (or penalisation) of specific meters, or sets of meters, straight-forward. A society may wish to subsidise (or tax) certain subsets of metered users, for example:

- *Vulnerable users*: E.g. a government could pay subsidies directly as deposits for identified meters.
- *By voltage level*: E.g. The fixed costs portion of the total payment could then be modified based on the network operation costs for the voltage level in question.
- *Accounting for exogenous socialised costs*: if groups of meters could be identified with technology that causes future socialised costs, those meters could be taxed (or all of the other meters subsidised).

A market for prediction of whole system need - Metered users can only achieve consistent rewards if they can both modify their usage and predict the whole system need. This creates a market for software tools that help predict the future state of the system and instruct the user devices (e.g. batteries) how to operate.

Increased incentive for Network Operators to predict well as the connections from a network operator to a higher voltage level are metered, and the meter is assigned to the network operator, the network operators have incentive to accurately predict the meter's usage (in addition to loss minimisation) and adjust their network to aid system balancing.

Increased security - division of responsibility for system stability into smaller network segments, together with the new responsibility for each network operator to maintain voltage in the event of any meter disconnections (including those to higher voltage levels), make the physical system more resilient to cascading voltage collapse.

Improved data for hosting capacity assessment and connection offers - As metered users are compelled to submit predictions, network operators have improved information to forecast the available hosting capacity for future connections at each node within their network. This can be used to map (and auction) network capacity for new connections in a transparent way using an approach from prior work [39].

Increased competition for the network operation role - the increased granularity of network operation licences also lowers the barrier of entrance for potential newcomers to the network operation marketplace.

Community energy options - The high granularity fragmentation of network operating licence areas gives the option of awarding network operator roles to a local communities, if all metered users agree (e.g. for a single Low Voltage feeder). In this case, the community has responsibility for its combined prediction (and therefore its reputation and rewards/penalties) in its connection to the whole system.

Competition amongst rule makers - The creation of a separate "rule making" role, which has responsibility for defining the rules of the economic game between meters, allows for competition in the discovery of rules (e.g. the exact rules for balancing commitment auctions). Such responsibilities are monopoly duties and can be tendered in the same way as network operation duties. A useful approach is the use of algorithm discovery competitions, such as the SHA-3 cryptographic hashing competition [36], to acquire a set of ruleset options.

Obsolescence of Supplier role In a GB context, the supplier role intermediates between demand and generation, has responsibility for some of the metering and performs customer service roles. Under these proposals, the demand-generation intermediation is done by the smart contract based automatically enforced economic rules. The responsibility for the metering is held by "meter operator" roles awarded at the governance level. Finally, the customer service function could achieved through the creation of one or more "system explainer" roles or through competition amongst user interface creators.

Reduced overall regulatory complexity By abstracting the whole system structure into physical, data, rules, and governance layers, and requiring both monopoly duties and energy flows to be negotiated within a multi-gate set of transparent negotiations, much of the system's physical and informational flows can be mapped within a single framework. This has the effect of reducing the regulatory complexity.

5. Conclusion

A new smart contract oriented whole system regulatory model for public electricity networks was presented. The model abstracts the system into four layers; physical, data, rules and governance. A set of roles was defined including "system governor", "rule maker", "network operator" and "meter operator". A framework of transparent negotiations that take place at multiple gates with respect to a usage period, followed by a settlement process, was presented.

Central to the model is the rules layer, where the ruleset defining the economic game between the metered users is instantiated. The use of smart contracts means that the rules can be automatically enforced and potentially lowers the implementation effort required to change them. This makes possible a competitive rules discovery process.

An example settlement ruleset was demonstrated that automatically rewards meters for useful contributions to system balancing. The rewards are paid for by the meters that make unhelpful contributions. A meter's rewards are modulated by its prior prediction based reputation, with unclaimed rewards accruing to network areas. This brings about a system wide Schelling point around system balancing and creates topologically linked incentive signals for prospective investors.

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8. Appendices

In this section, two negotiation algorithms are defined – for selecting from offers for energy usage and balancing commitments.

8.1. Negotiation of Energy Price

$\boldsymbol{Y}_{t,f} = \{y_{t,f,0}, y_{t,f,1}, y_{t,f,2}, \dots, y_{t,f,K}\}$ Set of K users making conditional energy offers lower than $PredictedImbalance_{t,f}$

$\boldsymbol{V}_{t,f} = (v_{t,f,0}, v_{t,f,1}, v_{t,f,2}, \dots, v_{t,f,K})$ List of K offered energy volumes from $\boldsymbol{Y}_{t,f}$ users, sorted by associated offer price and then, if prices are equal, by volume.

$\boldsymbol{O}_{t,f} = (o_{t,f,0}, o_{t,f,1}, o_{t,f,2}, \dots, o_{t,f,K})$ List of K energy price offers from $\boldsymbol{Y}_{t,f}$ users, sorted by offer price and then, if prices are equal, by associated volume.

$\boldsymbol{C}_{t,f} = (c_{t,f,0}, c_{t,f,1}, c_{t,f,2}, \dots, c_{t,f,J})$ List of J confirmed energy offer volumes for time window t at gate f

$\boldsymbol{\Upsilon}_{t,f} = (\varepsilon_{t,f,0}, \varepsilon_{t,f,1}, \varepsilon_{t,f,2}, \dots, \varepsilon_{t,f,J})$ List of J users with confirmed energy offers for time window t at gate f

$\boldsymbol{U}_{t,f} = \{u_{t,f,0}, u_{t,f,1}, u_{t,f,2}, \dots, u_{t,f,J}\}$ Set of J accepted price offers for confirmed energy offers for time window t at gate f

$PredictedImbalance_{t,f}$ The predicted imbalance of the whole system prior to acceptance of offers, see Equation (1).

$Threshold_{t,f}$ the discretionary threshold set by the system governor for time-window *t*, gate *f*.

Algorithm 1: Algorithm for picking energy offers
Input: $\boldsymbol{V}_{t,f}, \boldsymbol{Y}_{t,f}, \boldsymbol{O}_{t,f}$ $PredictedImbalance_{t,f}$, $Threshold$
Output: $\boldsymbol{C}_{t,f}$, $\boldsymbol{\Upsilon}_{t,f}$, $\boldsymbol{U}_{t,f}$
1: **for** i = 0 to J **do**

if $\left|PredictedImbalance_{t,f} + \sum_{c\in \boldsymbol{C}_{t,f}} c + v_{t,f,i}\right| < \left|PredictedImbalance_{t,f} + \sum_{c\in \boldsymbol{C}_{t,f}} c\right|$ **then**
$\boldsymbol{C}_{t,f} = \boldsymbol{C}_{t,f} + v_{t,f,i}$
$\boldsymbol{\Upsilon}_{t,f} = \boldsymbol{\Upsilon}_{t,f} + y_{t,f,i}$
$\boldsymbol{U}_{t,f} = \boldsymbol{U}_{t,f} + o_{t,f,i}$
if $\left|PredictedImbalance_{t,f} + \sum_{c\in \boldsymbol{C}_{t,f}} c\right| < Threshold$ **then**
return $\boldsymbol{C}_{t,f}, \boldsymbol{Y}_{t,f}, \boldsymbol{U}_{t,f}$
end if
end if
end for

8.2. Negotiation of Balancing commitments

$\boldsymbol{X}_{t,f} = \{x_{t,f,0}, x_{t,f,1}, x_{t,f,2}, \dots, x_{t,f,Q}\}$ Set of Q users making conditional balancing commitment offers at gate closure f, for time-window t
$\boldsymbol{B}_{t,f} = (b_{t,f,0}, b_{t,f,1}, b_{t,f,2}, \dots, b_{t,f,Q})$ List of Q offered balancing commitments from $\boldsymbol{X}_{t,f}$ users, sorted by associated offer price.
$\boldsymbol{\Theta}_{t,f} = \{\theta_{t,f,0}, \theta_{t,f,1}, \theta_{t,f,2}, \dots, \theta_{t,f,Q}\}$ Set of Q balancing commitment price offers from the set of Ut,f users List of Q energy price offers from $\boldsymbol{X}_{t,f}$ users, sorted by offer price.
$\boldsymbol{Z}_{t,f} = \{z_{t,f,0}, z_{t,f,1}, z_{t,f,2}, \dots, z_{t,f,J}\}$ Set of J confirmed balancing commitment offers for time window t at gate f
$\boldsymbol{\Omega}_{t,f} = \{\omega_{t,f,0}, \omega_{t,f,1}, \omega_{t,f,2}, \dots, \omega_{t,f,J}\}$ Set of J users with confirmed balancing commitment offers for time window t at gate f
$\boldsymbol{\Phi}_{t,f} = \{\varphi_{t,f,0}, \varphi_{t,f,1}, \varphi_{t,f,2}, \dots, \varphi_{t,f,J}\}$ Set of J accepted price offers for confirmed balancing commitment offers for time window t at gate f
$CommitmentVolume_{t,f}$ the volume of commitments set by the system governor for time-window *t*, gate *f*.

Algorithm 2: Algorithm for picking balancing commitment offers
Input: $\boldsymbol{B}_{t,f}, \boldsymbol{X}_{t,f}, \boldsymbol{\Theta}_{t,f}, CommitmentVolume_{t,f}$
Output: $\boldsymbol{Z}_{t,f}$, $\boldsymbol{\Phi}_{t,f}$, $\boldsymbol{\Omega}_{t,f}$
for i = 0 to J **do**
if $\left|\sum_{z\in \boldsymbol{Z}_{t,f}} z + b_{t,f,i}\right| > \left|\sum_{z\in \boldsymbol{Z}_{t,f}} z\right|$ **then**
if $\left|\sum_{z\in \boldsymbol{Z}_{t,f}} z + b_{t,f,i}\right| > CommitmentVolume_{\ t,f}$ **then**
$\boldsymbol{Z}_{t,f} = \boldsymbol{Z}_{t,f} + CommitmentVolume_{\ t,f} - \left|\sum_{z\in \boldsymbol{Z}_{t,f}} z\right|$
$\boldsymbol{\Omega}_{t,f} = \boldsymbol{\Omega}_{t,f} + x_{t,f,i}$
$\boldsymbol{\Phi}_{t,f} = \boldsymbol{\Phi}_{t,f} + \theta_{t,f,i}$
return $\boldsymbol{Z}_{t,f}$, $\boldsymbol{\Phi}_{t,f}$, $\boldsymbol{\Omega}_{t,f}$
end if
$\boldsymbol{Z}_{t,f} = \boldsymbol{Z}_{t,f} + b_{t,f,i}$
$\boldsymbol{\Omega}_{t,f} = \boldsymbol{\Omega}_{t,f} + x_{t,f,i}$
$\boldsymbol{\Phi}_{t,f} = \boldsymbol{\Phi}_{t,f} + \theta_{t,f,i}$
end if
end for
return $\boldsymbol{Z}_{t,f}$, $\boldsymbol{\Phi}_{t,f}$, $\boldsymbol{\Omega}_{t,f}$