Degrees of Freedom in Sharing Control of Smart Grid Connected Devices

A framework for comparison of cross-organizational control sharing mechanisms for balancing supply & demand

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Abstract**—Electricity networks require a balance between supply & demand of power in order to maintain stability and to provide a good power quality. The growth of renewable energy sources makes obtaining balance more difficult, because of their intermittent power profiles. Financial incentives for producing 'green electricity' locally also increase complexity due to the larger geographical distribution of electricity generation. Not surprisingly, more sophisticated (distributed) control mechanisms for balance in (smart) electricity grids are being proposed. Some of these proposals attempt to solve the problem of balance by managing demand, and thus introduce the concept of sharing control of devices connected to the grid. However, sharing control could introduce imbalances in 'societal' power between governments, companies and consumers. We propose that all parties involved should consciously decide on what amount of control they want to share. We provide a framework for comparison of control sharing mechanisms.**

Keywords-Smart grid; control sharing; privacy.

I. INTRODUCTION: WHERE DOES IT SAY SHARING IN 'GRID CONTROL'?

The concept of 'control of an electricity grid' can have different meanings. In this paper, we mean control with respect to obtaining balance between supply and demand of power in electricity grids. In an electricity grid, it is quintessential that the total consumption of power is continuously equal to the total production of power. If this is not the case, the quality of the provided power will degrade. In classic grids (as opposed to future 'smart' grids), control mechanisms are already put into place in order to deal with the variation in demand by power consumers. When consumers demand more power from the grid, power producing parties connected to the grid have to provide more power as a whole (group). In the future, more will be demanded from control mechanisms [11]. They have to be able to deal with the increase of more distributed and renewable power sources with variable output (wind, solar, wave, etc.).A solar cell or wind turbine cannot be powered down without wasting valuable energy. Also, wind turbines can not be immediately shut down by turning them away from the wind. Another problem is the fact that the power flow is changing from one way to two way. In the classic grid, there are a few 'centralized' large power plants and many distributed users. In future grids, there might be many distributed small power plants: home-owners with a wind mill, solar panels, geothermal installations, etc. that have a surplus in electricity production. This does not only reduce the accuracy of prediction the production of power – since it is now closely related to the weather–, but also the accuracy of the prediction of power transported across the grid, since locally generated electricity is consumed 'first' before more power is demanded from the grid. Another reason why more intelligence in the energy grid is needed, is that the rise of the usage of Plug-in (Hybrid) Electrical Vehicles (P(H)EV) seems to become a real challenge [12]. It is not unlikely that PHEVs will be plugged into the grid at almost the same time (when people come home from work). This will create a huge demand for power in a relatively short time, possibly resulting in a grid overload. The grid was not dimensioned with all this in mind. With the current grid it seems likely new control mechanisms have to be put in place.

Currently, 'Demand Response' (DR) of devices connected to the grid is being used in several research projects as a new means of control [13]. Depending on the amount of power that is consumed by devices, it can make sense to switch devices on and off in order to attain balance in the grid. Since DR almost always requires somebody or something else than the owner of the device to (automatically) switch on or switch off the device, device owners are no longer fully in control. For example, when DR is applied at charging PHEVs, the charging process may have to wait for a signal 'from the electricity network' that tells the car to start charging.

As a society, we should decide how much we want others to be in control of the grid-connected devices we own. For example, do we want to control our own devices in our own home, as we do now, or do we want having our devices controlled by some 'entity' in the electricity grid in order to have balance in the electricity grid? To make this decision we need a framework for comparison, which we provide in the remaining sections of this paper.

In the next section, related research on this topic will be given. We will see that much research is done, however almost no research is done in comparing different solutions with each other. After that, our problem description is given, followed by our contribution and methodology. Section V describes our framework, which can be used to compare different demand response mechanisms. After that, the consequences of choices in the framework are explained in Section VI. As an example of the application of our framework to a real situation, Section VII compares two real systems with each other, and mentions their differences. In Section VIII we will draw our conclusions, and finally, in Section IX, the future work will be described.

II. RELATED RESEARCH

The main goal of our research was to be able to compare control mechanisms for the management of supply & demand in smart grids. The comparison should be useful for different stakeholders in society. We want them to be able to decide on the application of these control mechanisms, based on the consequences for their societal position. We did not find research (yet) on that specific subject.

With respect to recent research on control mechanisms themselves we did find different approaches. First of all there is research with a focus on the control of the grid itself. In their description of a High Assurance Smart Grid (HASG) model Overman & Sackman put emphasis on the issue of admission control [1]. They describe a Smart Grid with '*a control system architecture characterized by a distributed architecture that is designed to mitigate against widespread failures when control system components themselves are compromised*'. More on this can be found a later paper from Overman et al., where 'a Three-Part Model for Smart Grid Control Systems' is described [3]. They note that while "*energy flow is now more interconnected and less hierarchical, the energy control system architecture is still largely hierarchical.*"**.** Furthermore, they elaborate on a distributed control signaling architecture "*such that some level of device collaboration can be done even when there are losses of control capability from the still dominant hierarchical control system architecture. This is a key feature required for a self-healing grid.*". We suspect that this will be an important aspect of future intelligent networks: distributed control, where no single entity has total control over the entire network. Not only because of the ability to deal with attacks on the network (which is an important aspect in the 'three-part model'), but also because of the fact that one or a few central entities cannot handle all the dynamics of supply & demand with energy sources with an intermittent profile.

Another example of what we think is innovative thinking in control of energy grids themselves, is described by Belkacemi et al. [6]. They use the concept of the Human Immune System (HIS) in order to "*perform self-healing and control of the grid by automatic fault location and isolation, reconfiguration and restoration*." They see the HIS as a Multi-Agent System (MAS), which consists of many different agents that carry out separate tasks with a certain level of autonomy, in order to achieve a goal at a higher level. There is no single control entity which is directly carrying out all control tasks, but control tasks are distributed across nodes. In this paper, however, we want to focus on sharing control between stakeholders. Grid stability and optimization is largely within the realm of a network operator. We also want to be able to take into account parties that the grid for 'energy logistics' and which (may) have to share control. There is also research carried out in this area. For example, an architecture for distributed control of power consuming and producing devices which are attached to the grid, is described by Tariq et al. [4]. They state that "*the advent of renewable generation technologies has resulted in increased complexity, requiring more powerful EMS applications. Regulatory changes in market structures frequently require modifications to these applications*". EMS meaning 'Energy Management Systems'. Next to stating this requirement, they "*describe the elements required for implementation of a "Prosumer" based distributed control architecture for smart grid*". In their description the authors describe four layers of control, that have no knowledge about the workings of the other layers and which only interact on the basis of interfaces between the layers:

- **Device Layer,** concerned with the physical connectivity of electric components.
- **Local Control Layer,** concerned with the control mechanisms of the devices. Examples named are the LTC control of a transformer and the battery charger of an electric vehicle.
- **System Control Layer.** According to the authors Energy Management Systems (EMS) and Distribution Management Systems (DMS) applications are examples of systems control layer for Independent System Operator (ISO) and electric utilities. Also the authors see 'corresponding' system control layers at the level of microgrids, buildings, homes, etc.
- **Market Layer**. Decision control processes at the level of available resources, where economic objectives are taken into account. This layer generates control actions for the system control layer or price signal for the external world, based on information from the system control layer, where market strategies are taken into account.

We state that the concept of 'layering' allows for a necessary separation of concerns, which enables us to deal with the complexity of future smart grids. Another model for control with separation of concerns is described by Molderink et al. [7]. They present a "*three-step control methodology….focused on domestic energy streams*". They refer to an important issue of sharing control from domestic environments: the comfort of residents. Different stakeholders in a smart grid have different goals and/or desires. While network operators might target at system stability, domestic users may ‘just’ want to have their devices consume energy in order to provide comfort. At the same time a government might want to target at reducing CO2 emissions by increasing energy (use) efficiency. This requires a combination of local and (more) global optimization. In their paper the authors provide three steps: local prediction, global planning and local scheduling. Together, these steps form one iteration. In this way, the authors think it is possible to combine different goals at different levels of control.

From a quantitative point of view one might state that controlling devices in a domestic environment will not be a real issue for the future since what amount of power can actually be shifted in time in homes? While this is an issue of debate (it also depends on the amount of electrification of heating and cooling equipment in homes), there is one development which certainly cannot be marginalized [10]. This is described by Erol-Kantarci et al. They state that the charging load of Plug-in Hybrid Electric Vehicles (PHEV) can cause several problems if left unmanaged. To that, they discuss an admission control system [8]. If everybody with a PHEV plugs in their PHEV after work, the grid has to transport a lot of power at the same time. Current grids have not been designed with this in mind. A (probably costly) solution would be increasing the capacity of the grid, another solution is to carry out some kind of ‘congestion management’ where PHEVs are charged ‘on-a-turn-basis’. This means sharing control, since the person wanting the PHEV getting charged is probably not the only one deciding on the time of charging if a congestion management mechanism is put into place. More on the important role of PHEVs or ‘gridable vehicles’ can be found in a paper from Venayagamoorthy, who talks about the complexity of Cyber-Physical Energy System (CPES) [5]. He does not only see ‘gridable’ vehicles as a consumer of power, but also as a possible producer. This adds an extra dimension of control to gridable vehicles, since this means two-way flow of power, making the control problem more complex.

III. PROBLEM DESCRIPTION

As stated at the beginning of Section II the main goal of our research was to be able to compare (distributed) control mechanisms for supply & demand management, based on consequences for ‘societal’ power. Our problem then became answering the question ‘what is an efficient and useful means of comparison – to be used by different stakeholders - with respect to sharing control of devices connected to the grid, when focusing on consequences for societal power?’

Answering this question required a structured overview of what we call the ‘solution space’: what kind of variations in Demand Response Management can be distinguished with respect to consequences for sharing control of devices connected to the grid and thus for societal power. To that we needed a overview of what the consequences would actually be when choosing for a specific model of sharing control.

IV. OUR CONTRIBUTION & METHODOLOGY

At TNO we are involved at different research projects, ranging from technical pilots, simulation studies economic evaluation of multi-stakeholder analysis, legislative view. We carry out this research on behalf of different customers. What we describe in this paper is derived from the experience we have had in these projects. The demonstration case “PowerMatcher” is a technology which we use in several other projects.

Our contribution in this paper is a framework for comparison, which contains a structured overview of the degrees of freedom for sharing control of devices connected to the grid. Also it contains a list of consequences caused by choices made with respect a certain degree of freedom. We arrived at this model by analyzing different (partial) Smart Grid designs from the viewpoint of sharing control, while focusing on consequences of design decisions. This resulted in the framework title ‘Degrees Of Freedom In Sharing Control’ (DOFISC) for Smart Grids (4SG). This approach resembles the approach we took in defining the DOFIS-4SG model, which was focused on ‘information sharing’ [1].

Like the DOFIS-4SG, the basic structure of the model is a set of axes. Each axis is a ‘degree of freedom’ and represents an aspect *controlling a device or a group of devices* of another owner. This means not all aspects of smart grid control are included. When control is within one domain of one owner (e.g. network operator), there is very little sharing going on, so these aspects are not taking into account. The aspects of sharing control we did include are related to differences in owner or user of a device connected to the grid. Just as with the DOFIS-4SG model, the basis for the included aspects was found in literature on Smart Grids and our experience with control architectures in other domains (i.e. telecommunications). We distilled the greatest common denominators and make additions where they were necessary in order to provide for making comparisons. And, once again, just as with DOFIS-4SG, this meant that we did not mathematically derive these aspects, but carried out a selection process based on the criteria 1) ‘relevant to control devices attached to the grid’ and 2) the axes being ‘orthogonal’. For more information on the concept of orthogonal axis see [1]. We arrived at a list of possible consequences in a similar fashion. Currently, we suspect that the axes, their subdivisions and the list of consequences can be used to assess and compare aspects sharing control of devices connected to the grid. Providing proof for this should be included in further research, just as it was the case with DOFIS-4SG, which is being evaluated at the moment.

V. FRAMEWORK DESCRIPTION

In this section, we present our framework, which can be used to classify and compare demand response management systems in smart grids. Our framework consists of 3 axes which are orthogonal to each other. An design choice on one axis does not influence an design choice on another axis. Before presenting the axes, we want to make a distinction with respect to different types of control of a device. We base this distinction on the three ‘modes of control’ of devices by Overman et al. [3]. With respect to devices *attached* (i.e. not *in*) to the grid we see three types of control:

1. **manual** control, A light that is switched on or off by home owners operating a switch. Another example is a electricity generator running on diesel. This type of control is difficult to share between parties which are not located at the location of the device.
2. **automatic** control, A light that is switched on by movement (e.g. infra-red sensor). Another example are solar panels that produce electricity once the sun is shining. This type of control is difficult to share between the owner of and others, because the control depending on the solar intensity.
3. **remote** control. A washing machine that is switched on by a control device outside the washing machine. This type of control can be shared, especially because of the fact that it is 'remote'.

Our focus in the framework is on remote control, which can be carried out from any location. Also, we understand sharing control to be the sharing of control between different persons and/or organizations. A network operator that uses distributed control mechanisms using multi-agent systems for 'network stability' does not automatically 'share' control with consumers. Only when the network operator has some (indirect) influence with respect to the control of power consuming devices, we consider this to be sharing control.

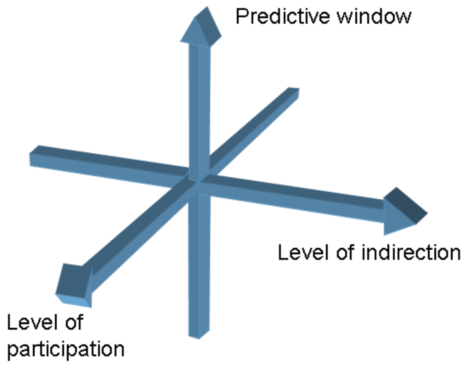

Figure 1. The three degrees of freedom

A. Predictive window

The predictive window is a time horizon of a controlling party. A controlling party has to make decisions and communicate them with others parties involved. It matters how far in advance the controlling party has to make its decisions. Some supply & demand designs prescribe a predictive window of 15 minutes, while others might have predictive windows of a day or even more.

An important question with respect to the predictive window is how far in advance does the controlling entity need to plan? For example, in Figure 2, if the controlling entity has a predictive window of 1 hour, it does not know that turning the washing machine on in 15 minutes, will cause a heavy load in 2 hours, when the electric car starts loading. However, if a controlling entity has a predictive window of three hours, it can foresee that starting the washing machine in 15 minutes, will cause a heavy load in 2 hours. And therefore, the controlling entity could make another decision.

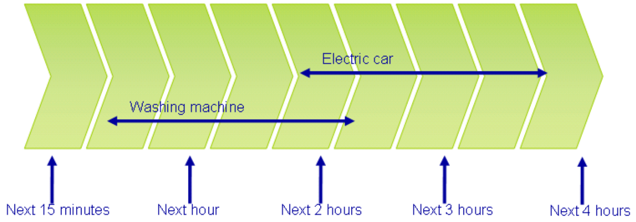

Figure 2. Distance in time

B. Level of indirection

The level of indirection determines the amount of freedom in control left after a control decision has been made by a controlling party. An extreme example is 'direct and total control', where the controlling party directly controls a device connected to grid.

There is a fundamental difference between direct control and indirect control. In case of direct control, the user is subjected to the control of the controlling party, and in case of indirect control, the controlling party gives directions with respect to power consumption. This can be in terms of constraints, within which is some freedom left to the consuming party to control devices connected to grid. Also a set point can be given as a direction, where the consuming party has to consume the specified amount of power. The controlling party does not specify which devices have to be switched on or off. An example of direct control is: a washing machine (2000 Watt) is turned on at 16:00, and the electric car (3000 Watt) will be loaded at 18:00. While an indirect example could be: the user will not be able to consume more than 3500 Watts. In both ways, the peak load is avoided, however in the indirect version, the user can chose to the order of the washing machine and the electric car. While in the direct version, the consumer has no choice. In any design of a smart grid, a decision has to be made about which stakeholders is in charge of making which (in)direct control decisions. Note that different stakeholders can provide different constraints to each other. For example, a supplier of power can set a maximum for the amount of power and a network operator can set a maximum for the amount of power which can be transported. In Figure 3, this concept is shown graphically. Three examples of possible solutions are shown:

- Red line: a supplier provides no constraints. The network operator is giving only high level constraints. And the direct control is given at device level.

- Blue line: a supplier is providing no constraints, the network operator is providing some constraints, the home environment provides more restrictive constraints, and finally, the direct control decisions are made at device level.
- Black line: the supplier is providing some constraints, and the network operator takes direct control decisions.

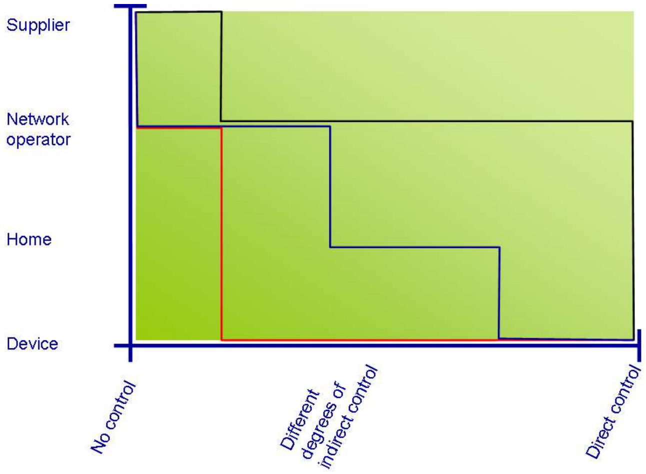

Figure 3. Level of indirection

C. *Level of participation in control decisions*

The level of participation is an important part of the control space. In different smart grid architectures, there are different levels of participation of owners of devices connected to the grid in control decisions. It is theoretically possible that the owner has no say in the control decision at all. For example, in the current energy network, in the Netherlands, no one is allowed to consume a peak load of more then 16 amps on one group of devices (each house can have several groups of devices). This control decision is based on the infrastructure (the infrastructure supports no more than 16 amps), and a consumer has no say in this decision (unless he is willing to pay for a special connection to the energy network). Another extreme is a smart grid, in which all consumers publish there preferences, and a distributed algorithm makes a control decision, satisfying as much as possible participants.

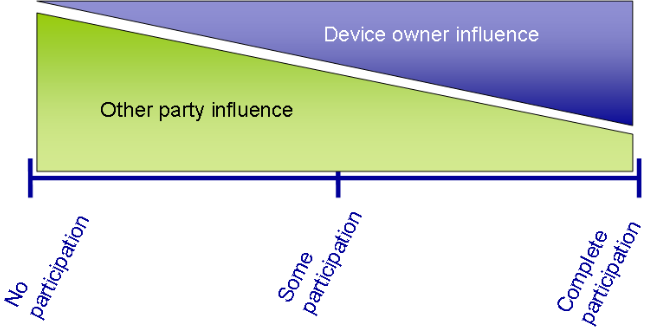

Figure 4. Level of participation

Note that a high level of participation differs from a high level of indirection. The level of indirection is about the decision itself (it is a property of the decision) While the level of participation is about the process of decision making.

In Figure 4, a graphical overview of the possible degrees of participation is provided. One extreme is no influence from owners/users of devices connected to grid, and the other extreme is almost no influence from another controlling party with whom control could be shared.

D. *Applying the framework*

To apply the framework, an inventory of all control decisions - made in a particular smart grid design - has to be made. Important for this phase is to recognize that there can be many different kind of decisions with respect to the control of power in one and the same design, so the framework may have to be applied many times in order to compare different designs. For example, one can imagine a design where parties make (indirect) control decisions: a power supplier who makes a control decision about the minimal load which is to be delivered, a network operator who makes control decisions about the maximal load, and a consumer who makes the direct decision to turn on device like a washing machine. In this case, at least three types of control decisions are made here.

To make things worse, a smart grid can have different ways to treat different devices. For example, to load an electric vehicle demand response management can be used, while for switching a lamp on and off, no demand response management is used. As a result, the framework may need to be applied multiple times to one architecture.

VI. CHOICES HAVE CONSEQUENCES

Choosing a position on the axis in the framework has consequences. In this section, we discuss consequences that relate to societal aspects of Smart Grids. We do not claim that this list is exhaustive.

A. *Consequences for balance of societal power*

The choices, which are made on one of the axes of our framework, have consequences. One of those consequences is the impact on the balance of what we call ‘societal’ power. With that we mean the power to determine the behaviour of other people and/or organizations. In the current energy grid, that kind of power is distributed. Each consumer has the right to turn his own devices on and of, and the energy suppliers take care of the energy balance on the net. Demand response management will affect this balance. As soon as control of the end used devices is shared with the network operators, the network operates will have more societal power in the energy grid, and the end user will have less. We do not put any direct qualification to a shift in the balance of societal power. We do want to state that a distributed balance of societal power is a natural barrier to misuse of power. In Table I, an overview is made of the impact the three axes of the frame work have on the balance of control. In this Table, it is shown how changing the position on one of the axes will have consequences.

TABLE I. CONSEQUENCES FOR THE BALANCE OF SOCIETAL POWER

Degree of freedom	Impact on balance of control
Predictive window	The size of the predictive window has a small impact on the balance of control. It determines how long in advance the controlling party has to make its decisions.
Level of indirection	The level of indirection has more impact on the balance of power. The more energy consuming and producing devices are directly controlled by one party, the more direct control this party has on the entire smart grid, and thus the people connected to it.
Level of participation	With a low level of participation, the controlling party has a high level of control, while a high level of participation will result in a lower level of control.

B. *Consequences for network stability and optimization*

In general increasing the degrees of freedom may seem to result in less network stability, or at least more difficulty in obtaining it. When more demands and wishes have to be taken into account, more sophisticated decisions have to be made. Whether or not this will be the case depends on the interaction of the actual control mechanism and the power consuming and producing behaviour of the different stakeholders. In this paper, we cannot provide the reader with a general 'rule-of-thumb' in this area. We can state that if network operators have no control at all and energy suppliers and consumers do share control with respect to balance in supply & demand, a situation could occur where there is balance in supply & demand from an energy point of view, but which cannot be implemented physically, due to network constraints. Also, by sharing control with a network operator, it could carry out more network usage optimisation and thus minimize the transmission costs. In any case, a decision on whether or not to share control with a network operator influences the possible usage of Demand Response to optimize network usage.

TABLE II. CONSEQUENCES FOR THE NETWORK STABILITY AND OPTIMIZATION

Degree of freedom	Impact on stability and optimization.
Predictive window	In a larger predictive window there are more possibilities for an optimization algorithm to find a optimal solution. For example, with a distance in time of 1 hour, it will not be possible to find a solution which involves a decision about another devices which has to be turned on in 3 hours. So, depending on the used algorithm for control, a large predictive window could result in a more stable and more optimized network.
Level of indirection	The impact of the level of indirection on the grid depends highly on the optimization and stabilization algorithms which are used. Some algorithms need a higher level of direction for a more stable and optimal network.
Level of participation	The higher the level op participation, the less influence of the optimization algorithms is used. Therefore, a higher level of participation will probably result in a less optimized and less stable network.

C. *Consequences for privacy*

The privacy discussion often focuses on the information which is gathered about the people. However, not only the information which is gathered about them influences the privacy. Also the amount of self-control influences privacy. In an extreme example: when all electricity is cut off after 22:00, most people will be forced to go to bed early. As a result, people have less control about their own live, and are forced to apply to the rules given by the smart grid. The different axes in the framework have different impacts on privacy. In Table III those impacts are explained.

TABLE III. CONSEQUENCES FOR PRIVACY

Degree of freedom	Impact on privacy
Predictive window	A large predictive window forces a consumer to make decisions about his energy consumption early. For example, when the decision to use no energy after 22:00 is made at 18:00, a consumer cannot change his mind at 21:00.
Level of indirection	The higher the level of indirection, the more choice the consumer has, so the lower the impact on privacy. For example, when the only control is that the consumer may not consume more than 3000 Watts, the consumer can decide for himself how he uses the 3000 Watts. However, when the grid decides that the consumer cannot watch TV, because he will be using the washing machine, there will be a huge impact on privacy.
Level of participation	When the control decisions are made by an external party, the owner of the device connected to the gird loses a lot of privacy. However, when the consumer is participating in the control decisions, the impact on privacy will be lower. The more participation there is in the decision making process, the more privacy *with respect to self-control* is left for the consumer.

D. *Consequences for green 'intermittent' energy*

Last but not least, we come to the consequences of sharing control for a driver behind 'smart grids': creating space for the integration of energy from renewable sources with an intermittent profile and limited prediction (wind, solar, etc.). When there is no sharing of control in the balance of supply & demand, attaining balance must be achieved by creating and or introducing other suppliers (e.g. more gas turbine based electricity plants) that can compensate for the variation on the 'intermittent' renewable supply side. Demand Response management (i.e. sharing control) reduces the need for extra flexible suppliers.

TABLE IV. CONSEQUENCES FOR 'GREEN' ENERGY

Degree of freedom	Impact on 'green' energy
Predictive window	A larger predictive window is difficult to obtain for power sources like wind and solar power plants.
Level of indirection	More or less indirection with respect to demand response management does not directly impact 'green energy'. However, when consumers are allowed to tell which energy resources have to be used ('green power'), direct control over the feeding of power to the grid does impact the use of green energy.
Level of participation	Sharing control for supply & demand management can be used to stimulate energy usage when renewable sources are 'at peak level'. However, a higher level of participation (be it consumers or produces) does not directly impact 'green energy'.

VII. FRAMEWORK APPLICATION

As a demonstration of how one could apply this framework, we now apply it in comparing the classical grid and *a* possible future smart grid with respect to sharing control of balancing supply & demand. For this grid of tomorrow we use the 'PowerMatcher' distributed control mechanism [9]. In a Powermatcher world there are so called consumer and producer nodes. They are represented by a 'software agents'. The agents exchange 'bids' on electricity. They express to what degree an agent is willing to pay (consumer) or receive (producer) for which amount of electricity. This is done through a mechanism based on micro-economic markets in which bids are aggregated and the market clearing price is determined as the equilibrium where supply meets demand. The 'market clearing price' is returned as a response to a bid. Agents then have to follow the allocated energy profile. Note that in the classical grid (in the Netherlands) a kind of auctioneering mechanism also takes place (e.g. the APX) at the level of Program Responsible parties (the electricity providers and network operators) The huge difference of the PowerMatcher lies within the fact that in a 'PowerMatcher world' devices attached to the grid partake into the bidding through their agents. We can now compare these two situations using the framework and focus on the consequences.

Predictive window. In the classical grid, consumers of power do not tell producers of their need for energy directly.. Only very large consumers have specific contracts with energy suppliers and network operators. For the mass of domestic and SME users statistics are used, where previous behavior is used to determine future behavior. In a PowerMatcher grid consumers do communicate their energy need – be it indirectly – by bidding prices for amounts of energy. The distance in time are market rounds. The distance in time is related to the time it takes for a market round to complete and if it is allowed to bid for market rounds in the future.

Level of indirection. In the classical grid, the consumer has a certain level of indirect control of balancing supply & demand. The entire group of consumers of controls the entire group of producers by demanding energy through the grid, which the producers have to supply, as long as the consumers pay. Since the price of energy for consumers hardly varies (in time), the amount of control of balancing supply & demand the producer has is very little. In a 'PowerMatcher world' there is more direct control from the producers: by demanding a higher price in the next market round, they can 'push' the agents of consuming devices into not consuming power. Or by lowering the price, they can 'push' agents towards consuming, depending on the actual need for energy of course.

Level of participation. In the classical grid there is little participation in control with respect to balancing supply & demand by both consumers and producers. The group of producers responds to a total predicted demand arriving at centralized markets (national, international). The group of consumers responds to prices on the market by energy providers. In a 'PowerMatcher world' the level of participation is increased significantly. Each consuming device influences the market (indirectly) by bidding and each producer influences the market by demanding a certain price for their electricity production. However, the amount of participation in a 'PowerMatcher world' is closely linked with the type of mechanism is used by the specific price determining agents used for determining the 'market clearing price'. For example, when real money is used in an auctioneering type of mechanism, the consumer willing to spend the highest amount of money available has more influence than parties who have less to spend. Also, producers demanding the least amount of money for their electricity will probably have more influence.

VIII. CONCLUSION

In this paper, we presented a framework for comparing (distributed) control mechanisms for balance of supply & demand, along three axes. The framework is focused on sharing control of 'end-user devices' in a smart grid. We saw that changes – along these axes - in the design of a control architecture for a smart will have consequences. We discussed these consequences with respect to issues of network stability, balance of 'societal' power, privacy and green energy. These issues are intertwined. For example, in an architecture, with a low level of indirection where energy suppliers can directly influence the usage of energy at consumers, a possibly unwanted consequence is the impact on privacy with respect to self-control. Increasing the level of indirection by having the energy suppliers influence the total amount of power instead of devices, the impact on privacy is less, but due to the shared influence of both the supplier and the consumer, there is more impact on network stability and optimization. Due to the possible large impact of design choices, we also argue that these design decisions should not be taken lightly. Future work

Although we already use the framework for comparison of control mechanisms for the management of balance of supply & demand in smart grids, we do think there is room for improvement. As the reader might have noticed the framework is not as fine-grained as it might need to be in order to make efficient and useful comparisons. Future work will have to determine if this is the case. To that, we want to integrate framework on ‘sharing control’ with our earlier framework on ‘sharing information’. We will be doing so in ‘Reference Model for Supply & Demand Management on Smart Grids’ (working title), which TNO is currently working on.

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REFERENCES

[1] G. Broenink, and K. Helmholt, “Degrees of Freedom in Information Sharing on a Greener and Smarter Grid” Smart Grids, Green Communications and IT Energy-aware Technologies (ENERGY), 2011 The First International Conference on , pp. 141-147, 22 May 2011

[2] T.M. Overman, and R.W. Sackman, "High Assurance Smart Grid: Smart Grid Control Systems Communications Architecture", Smart Grid Communications (SmartGridComm), 2010 First IEEE International Conference on, pp.19-24, 4-6 Oct. 2010

[3] T.M. Overman, R.W. Sackman, T.L. Davis and B.S. Cohen, "High-Assurance Smart Grid: A Three-Part Model for Smart Grid Control Systems," Proceedings of the IEEE , vol.99, no.6, pp.1046-1062, June 2011

[4] M.U. Tariq, S. Grijalva and M. Wolf, "Towards a Distributed, Service-Oriented Control Infrastructure for Smart Grid," Cyber-Physical Systems (ICCPS), 2011 IEEE/ACM International Conference on, pp.35-44, 12-14 April 2011

[5] Venayagamoorthy and Ganesh Kumar, "Innovative smart grid control technologies", Power and Energy Society General Meeting, 2011 IEEE, pp.1-5, 24-29 July 2011,

[6] R. Belkacemi, A. Feliachi, M.A. Choudhry and J.E. Saymansky, "Multi-Agent systems hardware development and deployment for smart grid control applications," Power and Energy Society General Meeting, 2011 IEEE, pp.1-8, 24-29 July 2011

[7] A. Molderink, V. Bakker, M.G.C. Bosman, J.L. Hurink and G.J.M. Smit, "Management and Control of Domestic Smart Grid Technology," Smart Grid, IEEE Transactions on , vol.1, no.2, pp.109-119, Sept. 2010

[8] M. Erol-Kantarci, J.H. Sarker and H.T. Mouftah, "Analysis of Plug-in Hybrid Electrical Vehicle admission control in the smart grid," Computer Aided Modeling and Design of Communication Links and Networks (CAMAD), 2011 IEEE 16th International Workshop on, pp.56-60, 10-11 June 2011

[9] M.P.F. Hommelberg, C.J. Warmer, I.G. Kamphuis, J.K. Kok and G.J. Schaeffer, "Distributed Control Concepts using Multi-Agent technology and Automatic Markets: An indispensable feature of smart power grids," Power Engineering Society General Meeting, 2007. IEEE, pp.1-7, 24-28 June 2007

[10] D.J.C. MacKay, “Sustainable Energy – without the hot air.” UIT Cambridge, 2008. ISBN 978-0-9544529-3-3.

[11] G. Strbac, A. Shakoor, M. Black, D. Pudjianto and T. Bopp, ”Impact of wind generation on the operation and development of the UK electricity systems”, Electric Power Systems Research, vol. 77, issue 9, July 2007 pp. 1214-1227

[12] C. Framer, P. Hines, J. Dowds and S. Blumsack, “Modeling the impact of increasing PHEV loads on the distribution infrastruction” System Sciences (HICSS), 43rd Hawaii International conference on, 2010, pp 1-10

[13] M.H. Albadi and E.F. El-Saadany, “Demand Response in Electricity Markets: An Overview”, Power Engineering Society General Meeting, 2007, Tampa, FL, pp 1-7.