EMERGING ELECTRICAL SYSTEM AS INTERACTING DYNAMIC MULTILAYERS COMPLEX SYSTEMS

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WHAT IS COMPLEXITY

DEFINITIONS OF COMPLEXITY

- “Complexity is that property of a model which makes it difficult to formulate its overall behaviour in a given language, even when given reasonably complete information about its atomic components and their inter-relations.”

  -- Bruce Edmonds, Syntactic Measures of Complexity [doctoral dissertation], Manchester Univ. 1999

- “Complexity: the greater the extent of inter-connections between components of a system, the more difficult it is to decompose the system without changing its behaviour.”

  -- RAMAMOORTHY, CV. An analysis of graphs by connectivity considerations. Journal of the Association of Computing Machinery, 1966, 13, 211-222.

- “Complexity in economics has simply meant not assuming that an economic agent acted as if it had the computational resources to completely cope with the demand placed on it by its environment.”

  -- HOLM, HJ. Complexity in Economic Theory. Lund, Sweden: University of Lund: Lund Economic Studies, 1993.

- “Complexity is the relations weaving the parts together that turn the system into a complex, producing emergent properties.”

  --Francis Heylighen. Complexity: 5 questions, Automatic Press/vip, 2008

DEFINITIONS OF COMPLEXITY

- "The philosophy of complexity is that this is in general impossible: complex systems...has properties -- emergence properties -- that cannot be reduced to the mere properties of their parts."

  --Francis Heylighen. Complexity and self-organization. Encyclopedia of library and information sciences, 2008.

- "Complexity can emerge in a system when the whole cannot be fully understood by analyzing its components."

  -- P. Cilliers. Complexity and post modernism: understanding complex systems.Psychology press, 1998.

- "Complexity is concerned with how the nature of a system may be characterized with reference to its constituent parts in a non-reductionist manner."

  --S.M. Manson. Simplifying complexity: a review of complexity theory. Geoforum 32, 405-414

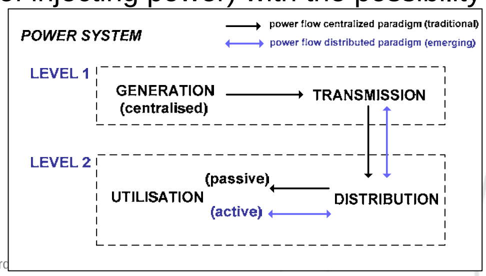
OUR UNDERSTANDING OF COMPLEXITY

"A system, that can be decomposed in a set of elementary parts with autonomous behaviors, goals and attitudes and an environment, is complex if its modeling and related simulation tools cannot be done resorting to a set of whichever type of equations expressing the overall performance of the system, in terms of quantitative metrics, or of a function on the basis of state variables and other quantitative inputs."

EMERGING COMPLEXITIES IN EES

EMERGING PARADIGM OF EES

- **Traditional paradigm**: four subsystems. ① Generation (centralized) ② transmission ③ distribution ④ utilisation. The first three subsystems are devoted to assure "quality electricity" to the fourth.
- **Emerging paradigm**, "generation" is no longer only associated to subsystem 1 (with a limited number of large-sized generators) but also with subsystem ④ as the users become "prosumer" (producer / consumers - huge number of small-sized generators from renewable sources). Subsystem ③ becomes active (capable of injecting power) with the possibility of bidirectional power flows.



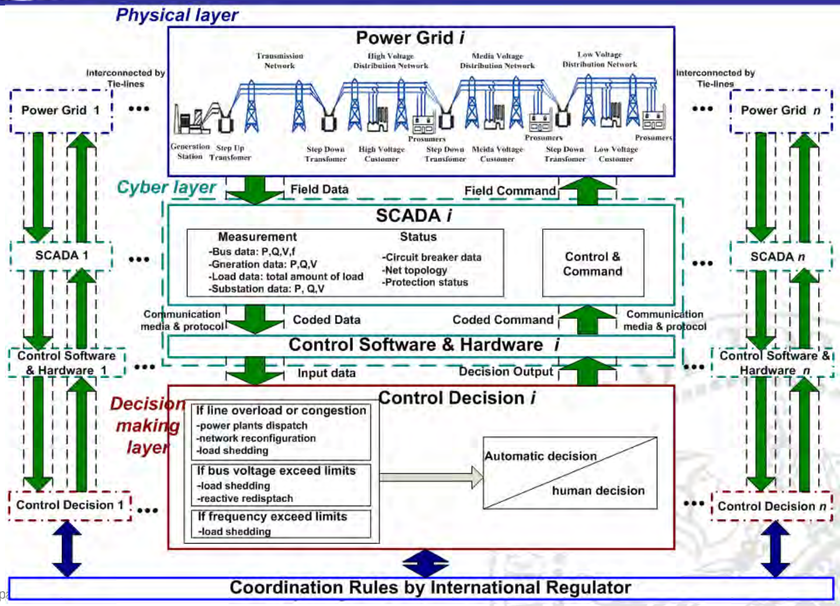
Level 1: Generation (centralised, large scale – hundreds of MW) + Transmission

Level 2: Distribution + Utilisation (small scale – down to KW)

EMERGING FEATURES

- Market structure based on *competition* (self-interested players interacting in competitive markets).
- Achievement of the objective of *energetic efficiency* and *environmental protection* based on market mechanisms.
- Aggregation of *distributed generation and storage* (small size, low predictable, connected to distribution system).
- Shift from centralised decision making (regulated monopoly) to *distributed decision making*, based on the maximisation of the individual utilities of a multitude of self-interested players that interact with a physically constrained network through various ICT technologies

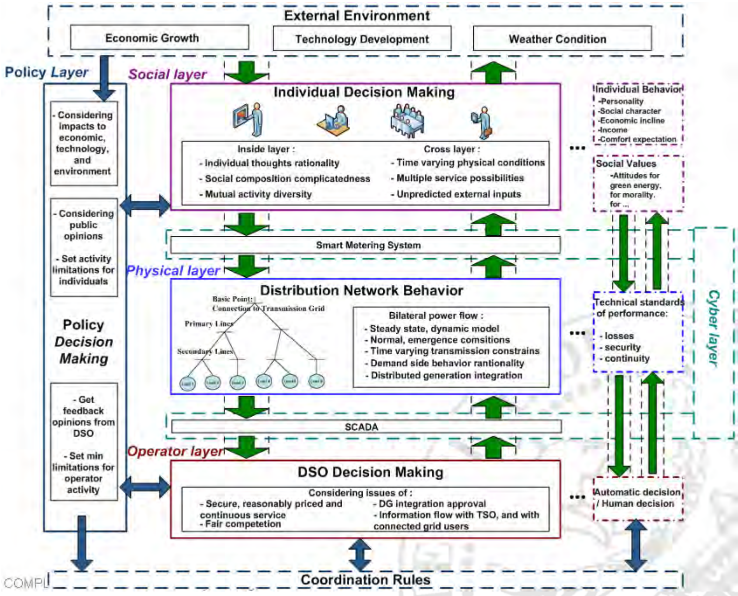
COMPLEXITY IN EES-LEVEL 1



COMPLEXITY IN EES-LEVEL 1

- The *physical layer* is the electrical power grid (wires, transformers, circuit breakers…) to transfer electrical power from generators to customers.
- Widespread impacts to the electrical network may result from decisions of system operators made in the *decision-making layer*.
- The *cyber layer* acts as an interface between the decision-making and the physical layers and vice versa.
- Electricity *markets* require efficiently exploiting available resources to supply customers, which causes more complex interactions within the above layers.
- The *performance* of the power system depends on a multitude of self-interested decision makers, each of them acting on a portion of the EU interconnected power transmission grid.

COMPLEXITY IN EES-LEVEL 2



COMPLEXITY IN EES-LEVEL 2

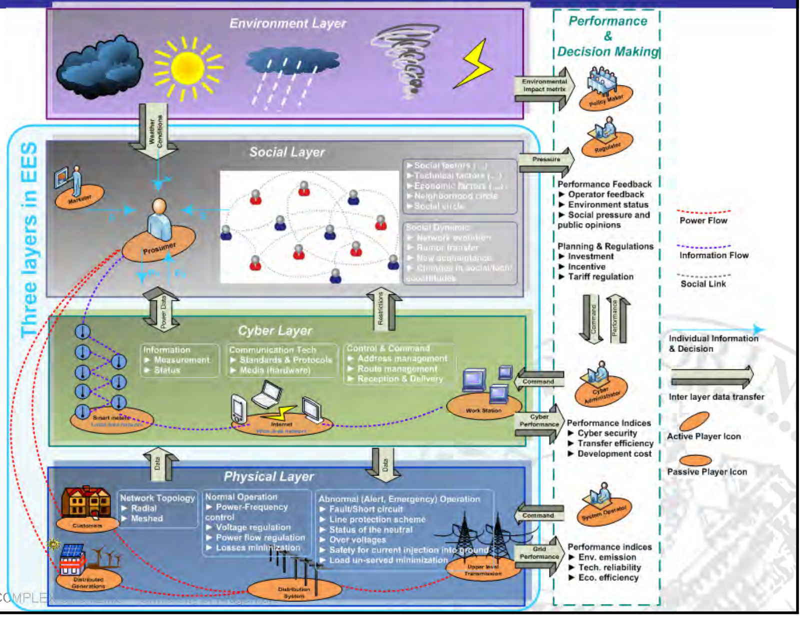
- *Distributed generations from renewable energy resources* such as wind power, solar energy, fuel cell and so on are drastically emerging and developing in Level 2 of EES.
- Shift in the paradigm from *"passive"* distribution, unidirectional flow (generation - final users) to *"active"* distribution with bidirectional flows with active users (prosumers).
- Emergence of bilateral power flow in Level 2 has enormously incorporated complexity into the *physical layer*.
- Initiatives have been laid upon the shoulder of traditional passive end-users, among whom tremendous *social complexity* can arise as a result.
- Appropriate sets of *policies and coordination rules* need to be set for the whole social welfare (economic growth, security and environment sustainability).

MULTI-LAYER EES AS COMPLEX SYSTEMS

EES AS MULTI-LAYER INTERACTING COMPLEX SYSTEMS (MLICS)

- EES operation and performances are related to various interacting aspects that may be *social*, *psychological*, *technical*, *economic* and *environmental*
- EES may be schematized by three layers: *social*, *cyber* and *physical*.
- The layers *interact among themselves and with external inputs* to determine the overall performance of the system that can be measured by *a set of meaningful metrics* (energy savings, environmental pollution, market efficiency …).
- The *overall "system control"* can be exerted only in terms of policy actions, implemented by laws and regulations (compelling, prohibiting, incentivising or de-incentivizing) to influence the behaviour of the various players.

MULTILAYER EES WITH EXTERNAL INTERACTIONS



LAYERS IN EES: PHYSICAL

- *Physical layer* is the layer in which power is flowing
- In the layer, are included power grids (radial or meshed) with (active and reactive) *power injection/withdrawal* at specific locations (nodes) which generated (real and reactive) power flow depending on the "electrical" *topology of the network* in terms of connections among nodes and their admittances.
- The grid needs to be operated under a set of strict *operational constraints* (voltage profile, max line flow limits, steady state and dynamic security constraints)

LAYERS IN EES: CYBER

- *Cyber layer* is the layer in which information for technical/economic operation are flowing over ICT supports.
- The operation of the grid relays on an ICT communication/command/control systems that *transfer technical data* for the field, in terms of digital and analogue information to human/automatic decision makers and, vice versa, *provide command and control action* to the fields.
- The *information exchange* is also key in a smooth functioning of electricity *markets* for real time price information (retail market) and *power exchange* operation (wholesale market)

LAYERS IN EES: SOCIAL

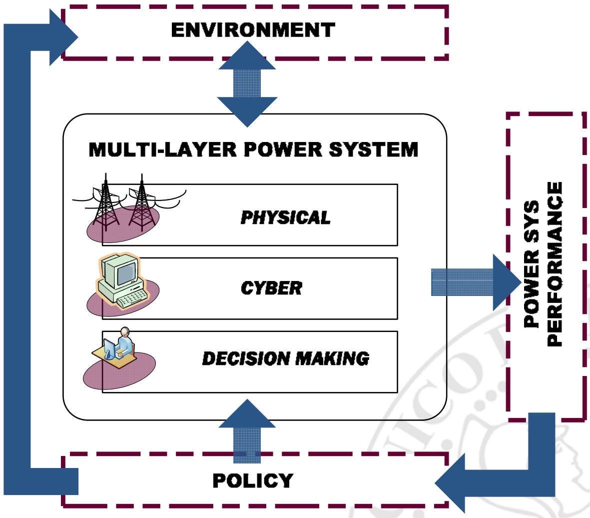
- Social layer: is the layer in which, individually and within a social network, people makes decisions
- The decision making incorporates human and automatic *procedure to control* the status of the players and their interactions with the system at various levels (from a national Transmission System Operator to a single prosumer) with reference to the *physical/economic flows.*

TIMEFRAMES FOR MULTILAYERS EES

- *In the short term* EES interact with an external environment, in terms of social, economic (market) and environmental conditions, subject to some constraints and incentives provided by the policy/regulation.

- *In the mid/long term* the change in the policy/regulation, considering possible changes in the environment strive for an improvement of the expected performances (economic efficiency, energy sustainability, security of supply).

EXTERNAL INTERCATIONS TO MULTILAYER EES



ENVIRONMENT AND POLICY/REGULATION

- *Environment*: encompasses various aspects that characterizes the external condition that *affect the performance* of the power system at a given point in time. Those conditions may *evolve more or less rapidly over the time*.
  - Some of the most relevant are: *technology* (options available for production, communication…), *market issues* (structure and design, billing and customer services) *social* (expectations, values and attitudes), *natural context* (natural renewable energy flows, weather conditions...).
- *Policy/regulation*: basically provides *“the rules of the game”* to the various decision makers in the power system.
  - In terms of *constraints* (security levels, emergency operations, environment of pollution,…) and *incentives* (rewards for green energy and quality of service).

PERFORMANCE

- Performance: is the *expected outcome* of the power system and can be measured by a set of *proper metrics* related mainly to economic, energetic and environmental issues.
  - Some examples of metrics are *social surplus*, allocation of surplus among producers and consumers, average price, market power indices (economic), *system losses*, production mix, share of renewable, energy intensity, to be clean or green (energetic), *level of "criteria pollutants"* such as nitrogen dioxide (NOx), carbon monoxide, ozone, lead, sulphur dioxide (SOx) and particulate matter (*environmental*).

COMPLEX ISSUES IN EES

- *Multitude of self-interested individuals* with different expectations and utility functions that provide a distributed decision making context with different goals.
- Policy makers, with considerations for global environment, energetic problems, social expectations, economic efficiency and security of supply, create a sets of targets, laws, rules and instruments for *achieving global goals*.

COMPLEX ISSUES IN EES

- Individuals with *constraints from policies and technical possibilities*, and with considerations of *economic terms* from the other parts of the system to decide on the behaviour of himself so that he can get what is needed as both easy and economic as possible.
- The system operator, operates with *constraints from policy makers and operational feasibility*, and considering gathered information and expectations from individuals, to do the most reliable and economical operation for the system.

COMPLEX ISSUES IN EES

- The distributed decision making interacts with the network structure with physical (Kirchhoff's law) and operational constraints defining its *(active and reactive) flows (flow networks).*
- The states of the system (feasible/unfeasible, secure/unsecure reliable and unreliable, stable and instable, vulnerable and resilient, survivable and un-survivable performance) built in real time and in medium/long term are *based on those distributed devices over its physical layer with a set of communication/control channels provided by its cyber layer.*

COMPLEX ISSUES IN EES

- The modelling of the system comprises the *model of each individual* (SO, DSO, prosumer…) *for the technical* (power profile, ICT channel …) and *economic* (profit, cost), defining a utility and interactions among themselves and with the cyber and physical layers. Providing study case and running simulation on the interactions within desired time frame, the *global performance can be forecasted.*

COMPLEX SCIENCE AS AN APPROACH FOR EES

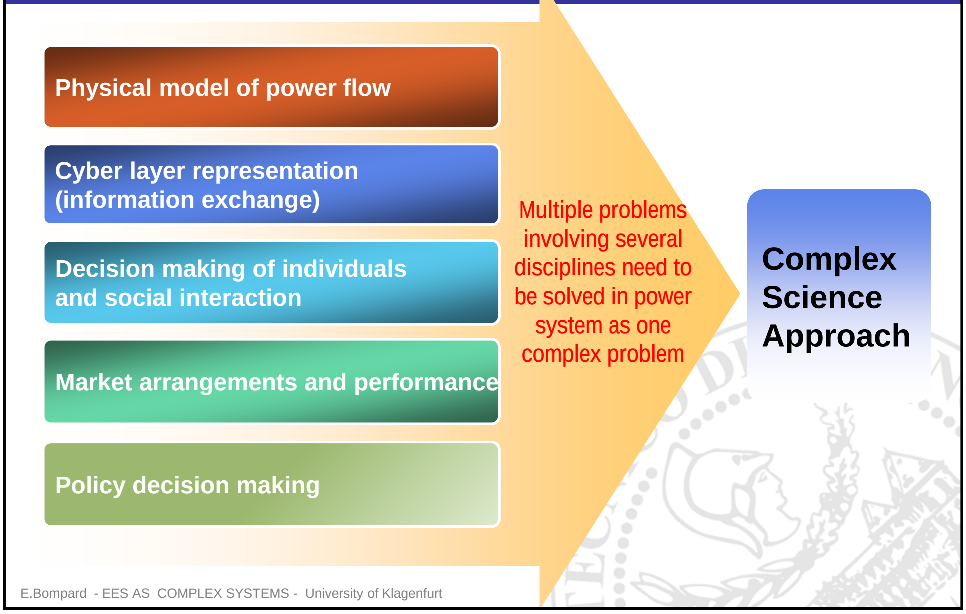
WHY WE NEED COMPLEX SYSTEM METHODOLOGIES IN EES

- Difficult to capture all the interactions with traditional «closed form» models (analytical equations).
- Traditional models are mainly focused only on one layer or in one of its subsets.
- Need for cross-boundary analysis in which the focus is more on the interactions (connecting variables) among the layers than on the layer itself.
- Provide a realistic simulation of the EES and their interactions (internal and external) as a tool for policy decision making support.
- Testing and assessment «in vitro» of legislative and regulation measures ex-ante

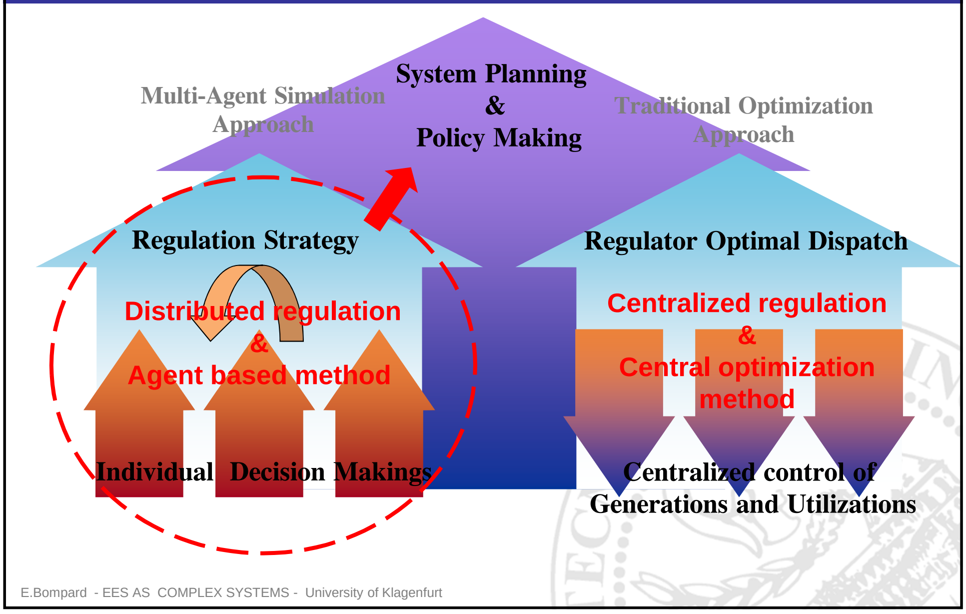
WHAT WE CAN DO WITH COMPLEX SYSTEM METHODOLOGIES IN EES

- Capture the interactions between the prosumers and the grid in EES, taking into account the social/technical/economic factors.
- The goals is to link the *social behavior* (psycho/economic) to the *network impacts* (technical).
- Simulation of *complex EES* with a large number of prosumers deciding for their own loads and distributed generations at the node where they are connected.
- Captcure *prosumer behaviors* under different social, technical, and economical conditions, and updating of attitudes through *interactions* among themselves.
- See what *system performance* would be with these prosumers' autonomous behaviors and especially with large penetration of distributed generations.
- Decide what *regulation rules* should be implemented and how to react to prosumers behaviors and optimize system performance and social surplus.

COMPLEX SCIENCE AS THE KEY FOR MODELING AND POLICY DM



COMPLEXITY FOR EES AND AGENT BASED TECHNIQUES



MULTI-AGENT SIMULATION AND ANALYSIS OF COMPLEX EES

THE FRAMEWORK FOR THE SIMULATION

- The simulation framework is built upon a stage named ESTS (*Environmental Social Technical System*);
- Various *players* whose actions form the progress of the play, act on that stage.
- *Directors* provide rules or instructions for the players, to direct player actions, guiding the whole play towards their ideal orientations (optimization).
- Looking to the *performance on the stage* the directors can check the progress of the play and provide new directions to the players.

THE STAGE: ESTS – ENVIRON. SOCIAL TECHNICAL SYSTEMS

- The ESTS provide inputs to the players, defines the possibility of interaction and suffers/enjoies the impacts of the play.
- (Natural) *Environment:* the weather conditions, states of natural resources, emission amounts,…
- *Social:* the network of people, their status in terms of profession/economy/technology/psychology, and the interactions among them.
- *Technical:* the facilities available for production electricity, for controlling the electric plants (smart building,…), the communication facilities.
- The *ESTS* is the stage over which the players interact according to the rules set by the directors.

ESTS DIRECTORS

- *Regulator* (REG – regulating agent). Public body in charge of issuing the rules and exerting the control over the electricity (and more generally energy) markets
- *Policy Decision Makers* (PDM – top decision agent). They are represented by the institutions, such as parliament, governments, ministries that choose the general goals and decide the policies

ESTS PLAYERS

- *Prosumers* (individual agents): persons, companies, institutions and organization that are connected to the distribution grid (MV and LV) in at least one point and that exchange bi-directional energy according to given power profiles continuously.
- *Distribution System Operators* (DSO- system agent): private organization that operated the distribution system with the goal to keep it feasible assuring some quality standards (continuity of supply, low voltage harmonic distortion,…). They charge to prosumers and marketers fees for "transporting" power/energy to/from the prosumers according to some pre-defined quality standards. Quality standards are fixed buy the Regulator and improvement/worsening of the standards may result in prizes/penalties to the DSO.
- *Retailers* (RET - market agents): companies whose core business is selling electricity at the retail market to the prosumers. They may own some power capacity and purchase electricity on the wholesale market.
- *Public acquiring companies*: state owned companies that provide incentivized prices.

INDIVIDUAL AGENT

- **Action set:** constrained by available technical options and social status, that define the dimension of the action set.
- **Communication with outside**: it makes materially possible to get information from other agents or environment willing to share their information; the communication represent the "fresh" knowledge that can be used to pursue the objective.
- **"Intelligence"** different degrees of intelligence, in terms of modelling, optimal decision making and learning are possible (zero intelligence agents choose purely random).
- With actions taken by an individual agent and feed back into ESTS, certain performances can be evaluated from external layers.

POPULATION OF AGENTS

- Properties of a population of agents are firstly decided by the **initial types and share** of each type of agent.
- With **time evolution**, aggregated actions from a population of agents can be **fed back** into the ESTS, performances can then be tested under scenarios.
- **Interaction** among agents of the same type, can be competition and cooperation; under social, economical, technical or political contents.
- **Intelligence** of a population of agents results into a system level optimization, under proper regulation.
- **Performance** of a population of agents can be in the sense of aggregated objective, or in the sense of ESTS optimization.

PERFORMANCE EVALUATION FOR DIFFERENT AGENTS

To Prosumers
- Bill savings
- Continuity of service
- Comfort level

To Distribution sys
- LV & MV network losses
- Voltage profile
- System overload
- Operational costs
- Security levels

To Transmission sys
- HV network losses
- Voltage profile
- System overload
- Operational costs
- Security levels

To Regulator
- Share of renewable generation
- Energy efficiency
- Market efficiency
- Average prices
- GHG reduction

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AN EXAMPLE OF MAS ANALYSIS OF MULTILAYER EES

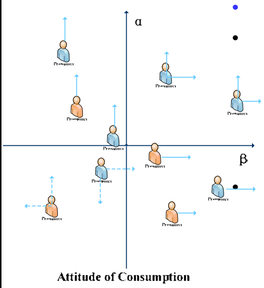
MODELING APPROACH AND KEY FEATURES

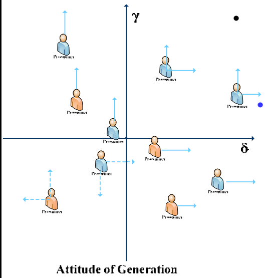
- The model is intended to capture the interaction between the prosumers and the MV/LV distribution system operator and regulator, taking into account the social intercation of prosumers, the physical specificity of the network as well as regulation methods provided by operator.

- The goal is to link the social behavior (psycho/economic) to the network impacts (technical) through models with the following features:

  - Social Model of individual prosumer: the prosumer is characterized in term of his /her psychological attitudes (decided by their social, technical, economic situations) toward consumption and generation
  - Physical Model of individual prosumer: power withdrawal and injection model, according to prosumers' attitudes
  - Model of social dynamics: how the prosumers interact among themselves (neighborhood circle and social circle)
  - Physical model of the distribution network: characterized as a flow network with the representation of key-variables (network flows, voltage profile, system losses,…)

SOCIAL MODEL OF THE INDIVIDUAL PROSUMER

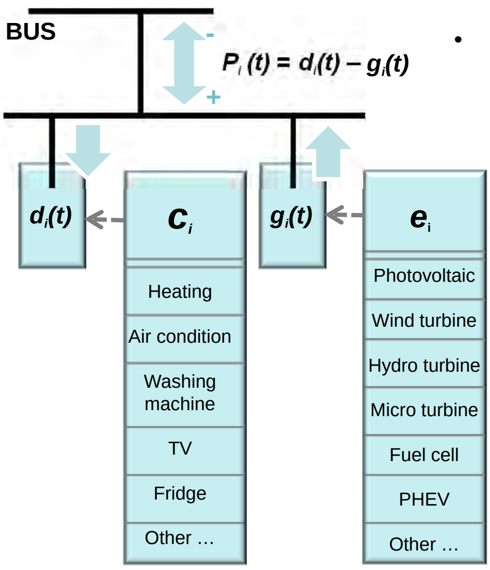




- **INDIVIDUAL SENSITIVITY OF EACH PROSUMER.**
- For ***consumption***, given in the short time a fixed level of power (appliances, devices, air conditioning, heating,..) the power consumption is driven by two factors:
  - α Comfort expectation (affects the amount of the available capacity the prosumer will effectively exploit)
  - β Demand price elasticity (responsiveness to price variation)
- For ***generation,*** given in the short time a fixed level of power (distributed generation sources, PV, Wind, FC,…) the power injection is driven by two factors:
  - γ Predisposition to technical management and attitude toward green energy (affects the amount of generation capacity effectively exploited)
  - δ Generation price elasticity (responsiveness to price variation)
- The individual behaviors can also be affected by
  - Inputs from the Environment (for example market price)
  - The social dynamics related to the interactions with other individual prosumers (agents).
- **SOCIAL SENSITIVITY OF PROSUMERS: THE WILLINGNESS TO CHANGE ATTITUDES**

Quadrant	Signs (x,y)	Rules
FIRST	(+ , +)	Sensitive to both attitudes of x/y axis to improve through interactions.
SECOND	(- , +)	Only care to improve the attitude of y axis
THIRD	(- , -)	Not influenced by other prosumers in their attitudes to consume and generate
FOURTH	(+ , -)	Only care to improve the attitude of x axis

PHYSICAL MODEL OF THE INDIVIDUAL PROSUMER



- Total capability of consumption c_i :
  - The available level of comfort for prosumer i
  - Can be measure by the sum of the power of all electric appliances and devices installed (kW).
  - c_i is fixed in the short time but can change in the middle(new appliances or devices might be bought)

Total installed capacity of generation e_i :
  - The available level of generation from prosumer i
  - Can be measure by the sum of the power of all generation devices installed (kW).
  - e_i is fixed in the short time but can change in the middle(new generators might be bought)

The demand can be expressed as :

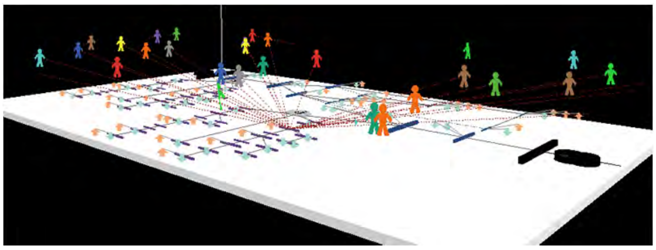
$$d_i(t) = | \alpha_i(t) | * c_i - | \beta_i(t) | * \rho (t)$$

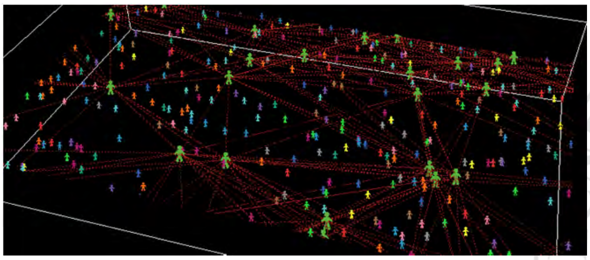
The generation can be expressed as :

$$g_i(t) = | \gamma_i(t) | * e_i - | \delta_i(t) | * \upsilon(t)$$

SOCIAL DYNAMICS MODEL OF THE INTERACTIONS OF PROSUMERS

Neighborhood circle: circle of prosumers connected at the same bus of the network





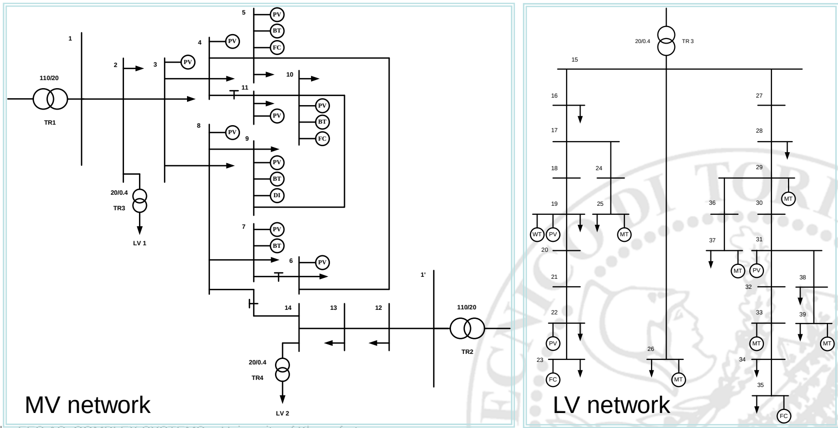
Social circle: circle of prosumers interrelated by some social links (workplace, clubs, churches,…)

SOCIAL DYNAMIC

- Individual behavior is affected by the behaviors of others.
- The influence of one prosumer over another can be executed only within social networks.
- We consider two social networks (Neighborhood Circle and Social Circle):
  - *Neighborhood Circle* is "spatial" and is related to the living place of the prosumers
  - *Social Circle* is "relational" and is related to the social connections of the prosumers
- The interactions are performed by:
  - A prosumer will firstly *evaluate rewards* (in the forms of comfort and cost saving) of other prosumers inside his social networks. Those prosumers with best rewards from both neighbourhood circle and social circle can be selected as a reference, adapting his/her behaviour toward the reference .
  - In the next time step, this prosumer will improve in the way of moving towards the middle direction of the reference for a fixed distance; thus *updating his attitudes* toward consumption and generation.

PHYSICAL MODEL OF THE DISTRIBUTION NETWORK

- Derived from from CIGRE Task Force C6.04.02: LV (0.4 kV) and MV (20 kV) distribution network, supplied by HV distribution network (132 kV)
- Power Flow computation
  - Problems: Bilateral radial power flow computation
  - Methods: Newton-Raphson & Backward/Forward Sweep



GOAL OF THE MODEL AND SIMULATION

- Simulation of the *complex LV/MV distribution system* with a large number of *prosumers* deciding for their own loads and distributed generations at the node where they are connected.
- Capture the pattern of prosumer *decisions on consumption and generation* under different regulation in terms of network charging methods, and the *changes of decisions* owing to updated attitudes through *interactions* among themselves in both their neighbor hood circle and social circle.
- Generate *performance curves* in the indices of power loss, outrange voltage, reverse power flow and distributed generation rate; thus see what the system would be with these prosumers' autonomous behaviors and interactions.
- Compare from the three *ways of charging the distribution service* and see how the *indirect optimization* of a MV/LV distribution system (especially with large penetration of distributed generations) should be done through *direct injection of real time information* to the social layer.

EXEMPLIFICATIVE CASE STUDIES

- Case I: Prosumers with DG in DS

  The basic scenario illustrating how the social and physical layers are connected by each other; and how the evolution of dynamic prosumer society affect distribution network performance. The irrationality of the prosumer society is captured with its impacts towards the distribution network.

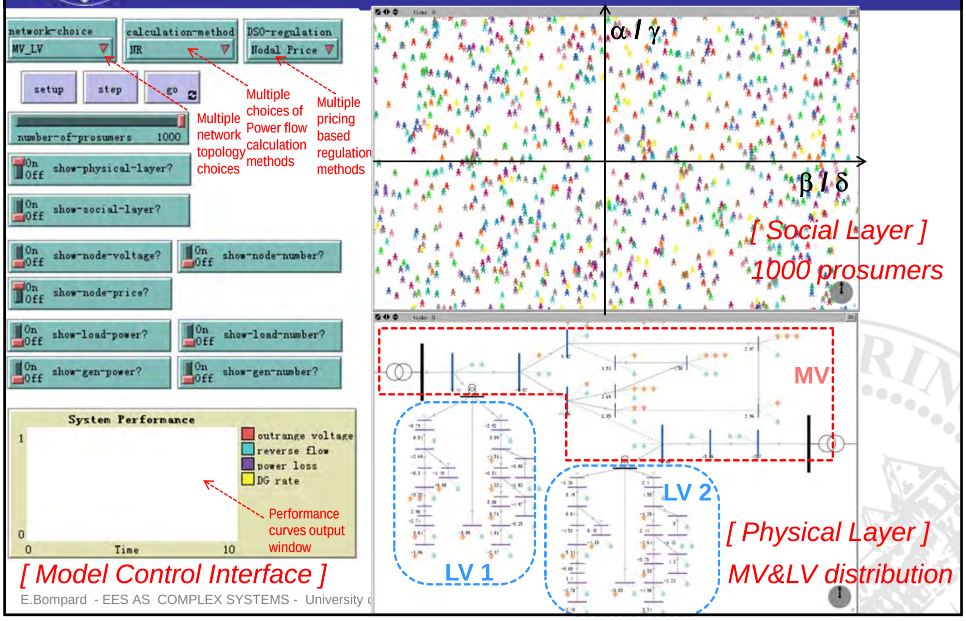
- Case II: Network Charging

  Network charging is used as a signal to regulate prosumers towards better consumption and generation behaviors (from the network regulator's point of view). Different charging methods are tested and compared with each other, and a dominate locational charging is adopted as the best regulation strategy.

- Case III: Market Validation

  The price paid by the prosumer depends both on the network charging and the retail electricity (which is not under control by the regulator); which role can still play the network charge? A 24-hour periodic demand with retail pricing are tested under different regulatory charging.

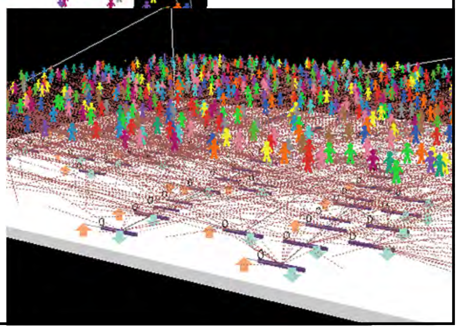
IMPLEMENTATION OF THE MODEL (NETLOGO)



Case Study I: *Prosumers with DG in DS*

[3D view with both Physical and Social layers]

[prosumers linking with their nodes]

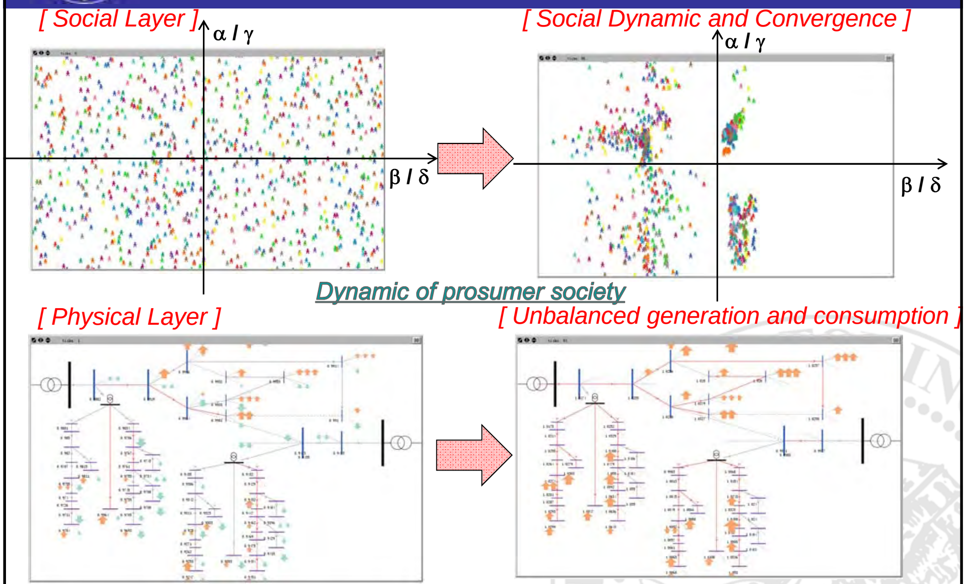


[social]
Prosumer layer

[Physical]
Distribution system layer

A 3D view of the game

Case Study I: *Prosumers with DG in DS*
SIMULATION RUNNING



Dynamic of prosumer society

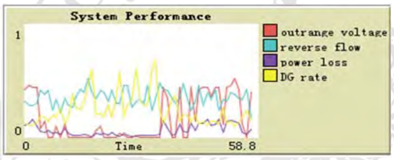
Evolving distribution system

Case Study I: *Prosumers with DG in DS*
SIMULATION RESULTS

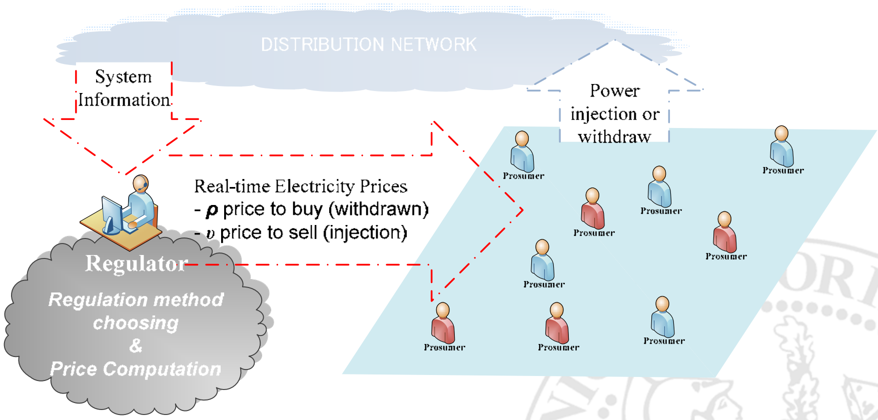
- Physical *load and distributed generation* amounts in distribution system layer are *decided by prosumers* connected with this node in real time. *Real time power flows* according to this aggregated decision are then calculated.
- Maximum of 1000 prosumers with different *initial value senses* (x/y coordination in the layer) *and professions* (color in presentation) are generated with a equal degree of randomness. Value sense according to the coordination in the layer were introduced in the page of *prosumer utility choices*.
- Prosumers constructing the *social network* are *interacting* with each other in decision making both according to their life circle (neighbors besides them) and their business circle (with same color), in the form of moving towards the prosumers they select as a reference, thus *changing their value senses and adopting the strategies* in the next time step.
- By the *convergence of prosumers* in social layer, *physical* consumption and generation are *evolving* from over-consumption to energy balance to over-generation, as can be seen from previous video games.

[System Performance]

- In the first quarter of *system performance*, outrange voltage rates are vibrating because of initial randomness; in the middle part, social cognition results in improved voltage profile; while as prosumers get converged, a trend of over generation or over load is observed in this distribution system.



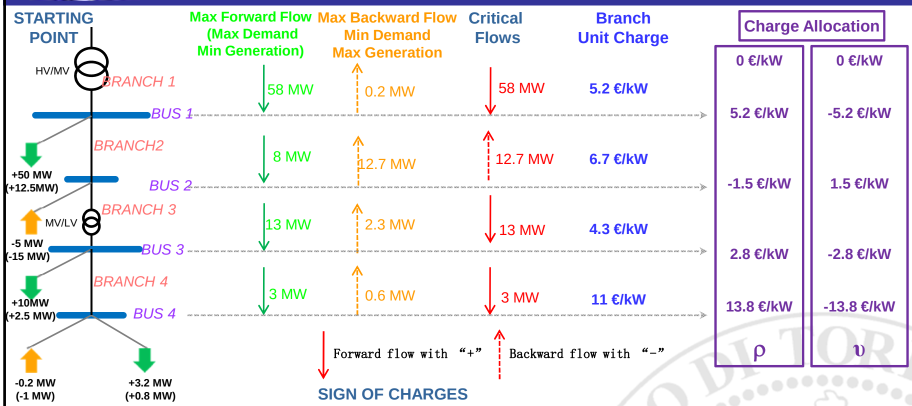
Case Study II: *Network charge*



Case Study II: *Network Charging*
CHARGING METHOD

- **Step 1**: *System description*
  - Network structure, Load / Gen profile
  - Each prosumer with a degree of arbitrariness (according to attitudes of comfort and price)
- **Step 2**: *Critical loading*
  - Two states of max gen min load and min gen max load predicted are computed respectively.
  - Critical loading for each branch is taken as the maximum flow under the two system states.
- **Step 3**: *Sign of charges*
  - Power flow directions driven by prosumers in accordance with critical loading pay for what the inject or withdraw; conversely get paid.
- **Step 4**: *Calculation and allocation of network charges*
  - Network costs for all upstream branch levels are added according to the polarities as the unit charge for prosumers (for their consumption and generation respectively) in each node.
- **Step 5**: *Evaluation of charges*
  - Charges for each prosumer are computed according to their decisions in the next time period consumption and generation.
  - This charging information will be sent back to prosumers, objections issued by any single prosumer will be taken and iteration of this pricing process will be carried out until no adjustments from prosumers are taken.

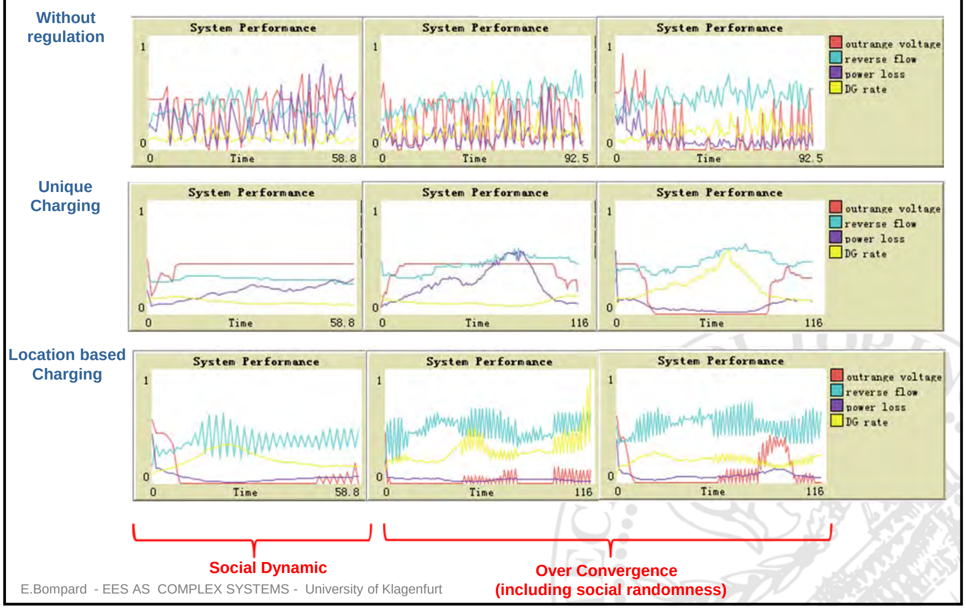
Case Study II: *Network Charging*
NODAL CHARGE EXAMPLE



SIGN OF CHARGES

	BRANCH			
	1	2	3	4
Critical Flow	+	−	+	−
Load on bus1	Pay	0	0	0
Load on bus3	Pay	Get Paid	Pay	0
Load on bus4	Pay	Get Paid	Pay	Pay
Gen on bus2	Get Paid	Pay	0	0
Gen on bus4	Get Paid	Pay	Get Paid	Get Paid

Case Study II: *Network Charging*
PERFOMANCE COMPARISON

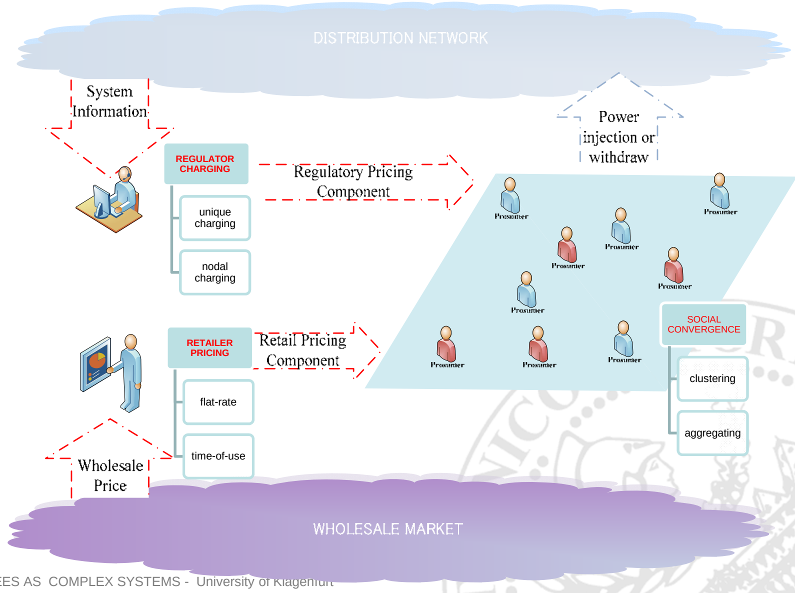


Case Study II: *Network Charging*
RESULTS OF NODAL PRICING VS. OTHERS

- For better understanding of the benefit from location based charging introduced, we also take unique charging as a comparison. Unique charging is a charge allocation with common prices for all nodes in the system computed from whole system costs.

  Thus taking no regulation through network charging as a basic scenario, comparisons of the three scenarios can be concluded as following:
- With the impact from dynamic behaviors of prosumers following the same style of reaction to charging signals, both charging strategies have the effect of *stabilizing the system performance* as well as *preventing enormous outrange situations*.
- Unique charging failed to reduce outrange voltages and power loss compared with location based charging, which *minimized these two indices* all through the dynamic process.
- DSO nodal pricing showed a characteristic of *efficient reaction* through over converged prosumer society (when performance indices are always worsen because of over loading or over generation of prosumers behaviors), it seems that DSO nodal pricing is the only case that *rectified this irrationality* of prosumer behaviors in a few steps.

CASE STUDY III: *MARKET VALIDATION*



CASE STUDY III: *MARKET VALIDATION* RETAILER PRICING IN 24-HOUR

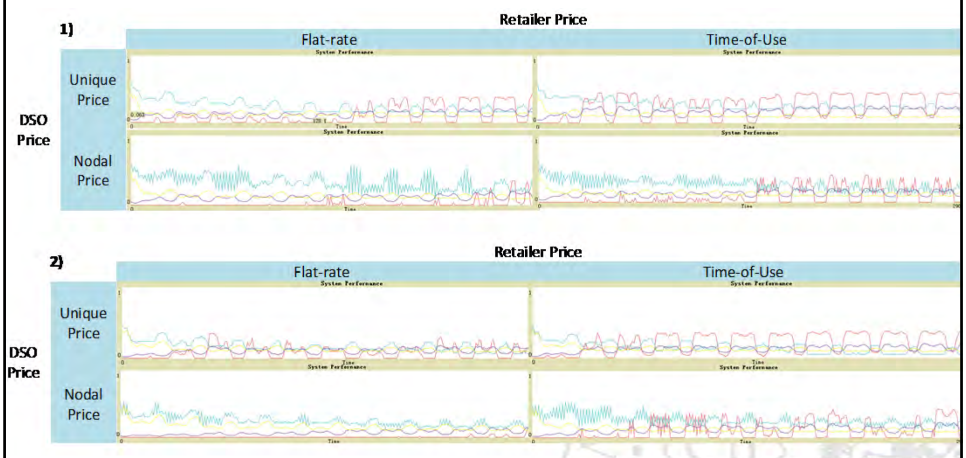
- Other than the regulatory pricing signals from DSO, prosumers are also charged for their energy consumption according to competitive market players (here represented by retailer's *Flat-rate* and *Time-of-use* pricing).
- The power profile varying over the time with different power injection/withdrawal hour by hour may affect the outcome of the regulation thus *24-hour demand profile* is also considered in this case study.
- **Will DSO's network charging still be effective for regulating prosumer behaviors in competitive market with different retailer pricings and time-varying demand?**
- Hereby we tested the performance under four combinations of regulator and retailer pricings in a 24-hour profile.

Case Study III: *MARKET VALIDATION* SOCIAL CONVERGENCE PATTERN

- Two patterns of social convergence are taken into consideration:
- *a. Clustering pattern*, prosumers' psychological attributes, although are influenced by one another, will not get exactly the common sense in electricity consumption and generation (clustering in social layer);
- *b. Aggregating pattern*, a commonly recognized (by prosumers) optimal attitude towards electricity consumption and generation is adopted by all prosumers, thus getting an extremely identical power withdraw and injection
- Clustering pattern are more realistic for understanding the daily behavior of prosumers under both regulated and competitive markets, while aggregating pattern though not necessarily would happen in real world, will show potential possibilities of system performance as extreme trends of clustering society.

Case Study III: *MARKET VALIDATION* PERFOMANCE（1）

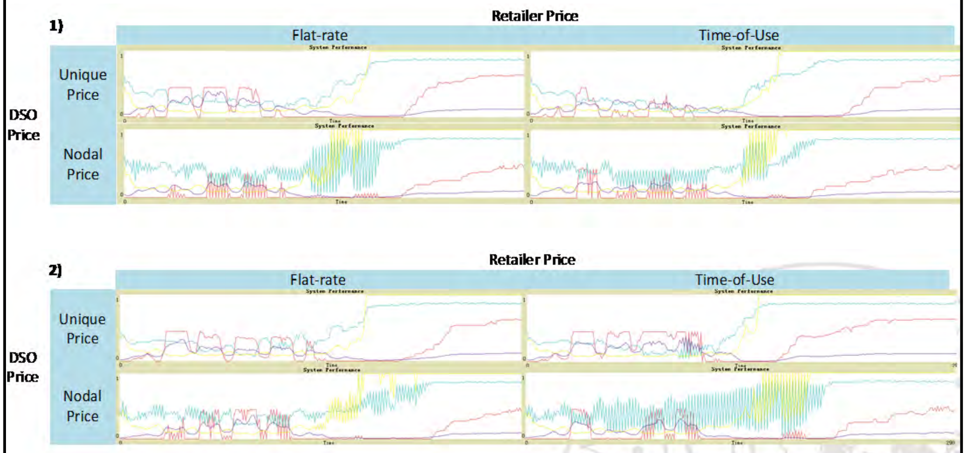
Clustering society



[Note] Outrange Voltage rate: preferred voltage range are set 0.9 to 1.1; this index measured the percentage of nodes with an voltage out of this range;
Power loss: losses in this MV/LV network are added and unified to compare;
DG rate: presents the ratio of power consumption that comes from local generation;
Reverse line flowrate: this index measures the rate of lines with reverse line flows;

Case Study III: *MARKET VALIDATION* PERFOMANCE （2）

Aggregating society

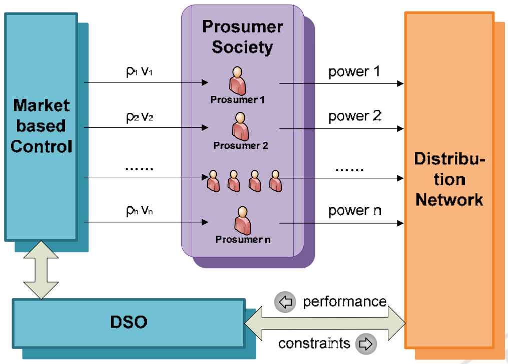


[Note] Outrange Voltage rate: preferred voltage range are set 0.9 to 1.1; this index measured the percentage of nodes with an voltage out of this range;
Power loss: losses in this MV/LV network are added and unified to compare;
DG rate: presents the ratio of power consumption that comes from local generatio;
Reverse line flowrate: this index measures the rate of lines with reverse line flows;

Case Study III: *MARKET VALIDATION* PERFORMANCE COMPARISON

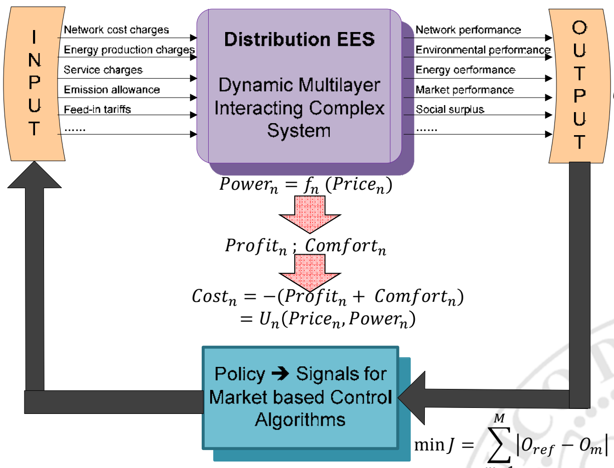
- Mostly, *nodal pricing will still be recognized a better choice* with comparison with unique pricing in network charging from DSO in same conditioned competitive market.
- *Irregular situation*: in some case, the market scheme combined by retailer time-of-use pricing and DSO nodal pricing is actually worse behaving than the market scheme combined by retailer time-of-use pricing and DSO unique pricing; though observing the same case in aggregating society, we can still recognize the former market scheme better than the latter.
- *In the process of SG penetration, best regulatory choices for different SG developing levels can be made and dynamically adapted along with the SG penetration*.
- These situations are just the reasons for using ABM as the ex-ante policy testing tool. Other than one ultimate optimal policy that can be decided in a mature Smart Grid environment, ABM can recognize a set of evolutionary regulation measures suitable for different technical conditions and developing periods.

Case Study IV : Market based control



- Market based Control under this situation contains two objectives:
- To set up reasonable market structure, and under this structure to regulate prosumers towards better performance in every aspect concerned by the regulator;
- For example, taking concerns from the DSO, the objective of regulation can be better performance in distribution network indices.

Case Study IV : Market based control



$O_m = F_m(Price_n, Power_n)$

$Power_n = f_n(Price_n)$

$Profit_n\ ;\ Comfort_n$

$Cost_n = -(Profit_n + Comfort_n) = U_n(Price_n, Power_n)$

$$\min J = \sum_{m=1}^{M} |O_{ref} - O_m| + \sum_{n=1}^{N} Cost_n$$

s.t.

$\sum P_i = 0$

$V_i^{min} \le V_i \le V_i^{max}$

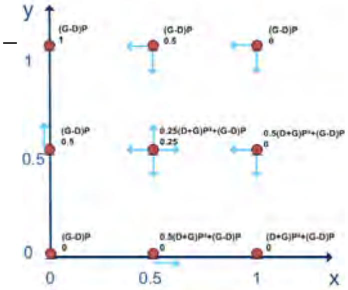
$P_j^{min} \le P_j \le P_j^{max}$

$Q_j^{min} \le Q_j \le Q_j^{max}$

Response over MBC

- Prosumer decision making
  - $Power_n = Demand_n * [1 - Price\_C_n * x_n * (1 - y_n)] - Gencap_n * [1 - Price\_G_n * x_n * (1 - y_n)]$

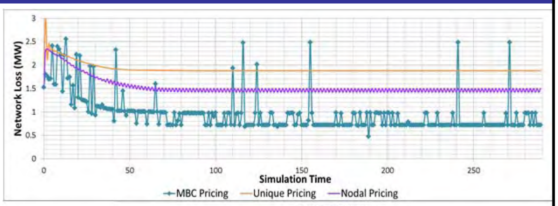
  $Price\_C_n = -(Price\_G_n)$, represented as $Price_n$.
  - $Profit_n = -Price_n * Power_n = (Demand_n + Gencap_n) * x_n * (1 - y_n) * (Price_n)^2 - (Demand_n - Gencap_n) * Price_n$
  - $Comfort_n = y_n * (1 - x_n)$

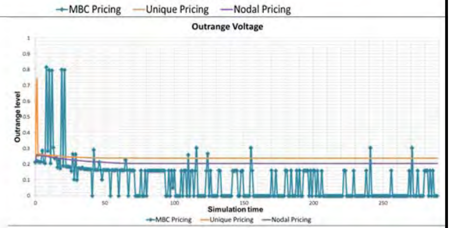


- Interaction and convergence
  - $\Delta Benefit_n = x_n * \Delta Profit_n + y_n * \Delta Comfort_n$
  - Convergence at (0,1) and (1,0)
- Market control forces and sensitivity
  - $d' = d_0 + vP + aP^2$
  - Market driven accelerated velocity $(Demand_n + Gencap_n) * x_n * (1 - y_n)$
  - Market driven accelerated velocity $(Gencap_n - Demand_n)$

Case Study IV: Performance of Distribution Network

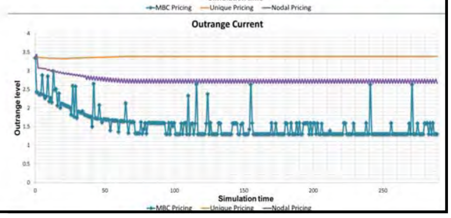
- By giving three types of network pricings: ***unique pricing, nodal pricing*** and ***Market Based Control (MBC) pricing***, are the most direct indices of network performance in terms of loss, voltage level and line flow are shown :





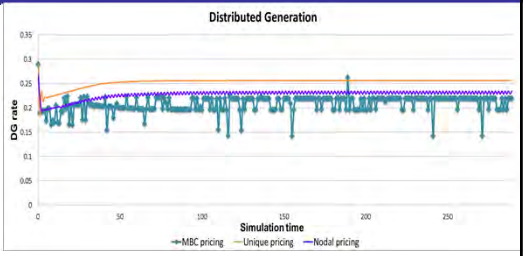
- MBC pricing is recognized with the most superiority, especially as simulation goes by, when prosumer society is converging, the differences of performance are getting more obvious accordingly.

- Though on the performance curves of MBC pricing, a few points were dropped out of the regular trace as a result of ex-ante pricing and instant strategic responding proumers; moreover, these points were dragged back by MBC pricing to the normal rate of performance quickly enough for the next simulation time.

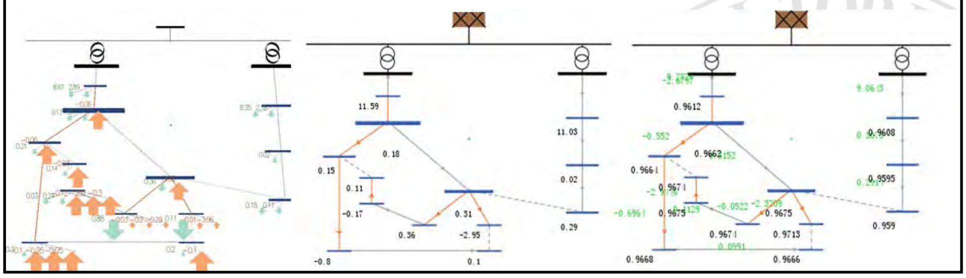


Case Study IV: Performance of Distribution Network

- On the DG rate figure MBC pricing has achieved the best network loss, voltage and current performance using the least distributed generation input from the prosumer side.
- Level of DG utilization under best utilization (generation in orange, and loads in green), which suggests indirectly the best placement of distributed resources over the network taking into consideration of prosumer behaviors
- A few branches recognized with reverse power flow (marked in orange), which may be the most desirable branches for network enhancement.



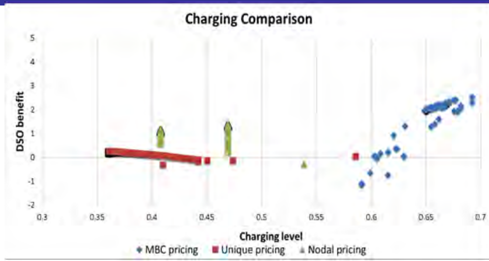
- Bus voltages (in black) and line currents (in green) are shown with some violent values indicating corresponding protection procedures.



Case Study IV: Performance of Market participants

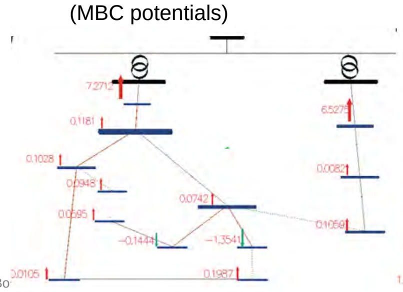
- DSO Benefit

Unique pricing and Nodal pricing compared with MBC pricing, both showed a lower level of charging with little benefit (or even negative in Unique pricing); even increasing the charging level didn't seem to work for increasing DSO profit (Unique charging with a decreased profit while increasing charging level, and Nodal pricing seems more or less unchanged).



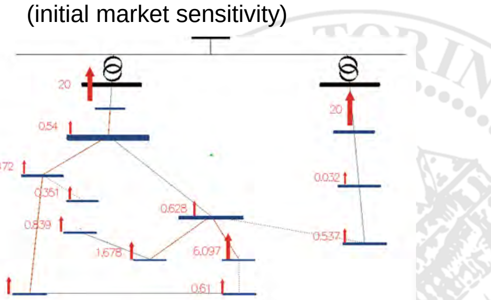
- Marked driven acceleration

(MBC potentials)



- Initial velocity

(initial market sensitivity)



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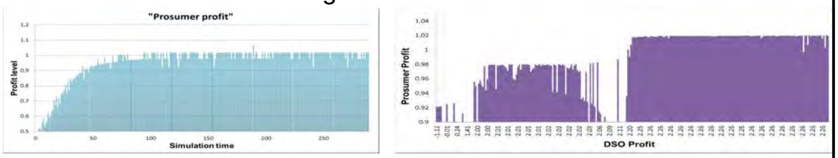
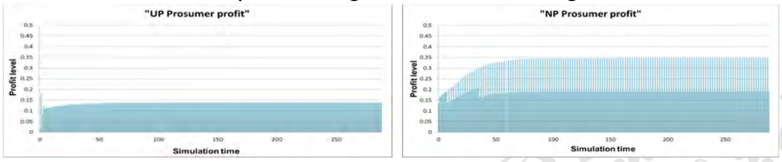
Case Study IV: Performance of Market participants

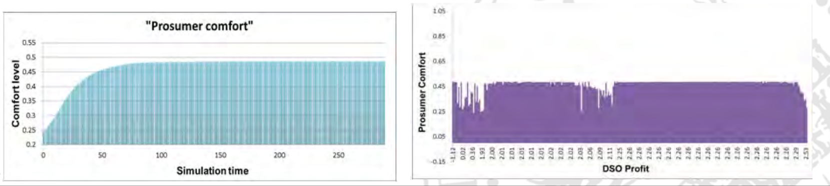
- Prosumer Profit under MPC Pricing



- Prosumer Profit under Unique Pricing and Nodal Pricing



- Prosumer Comfort

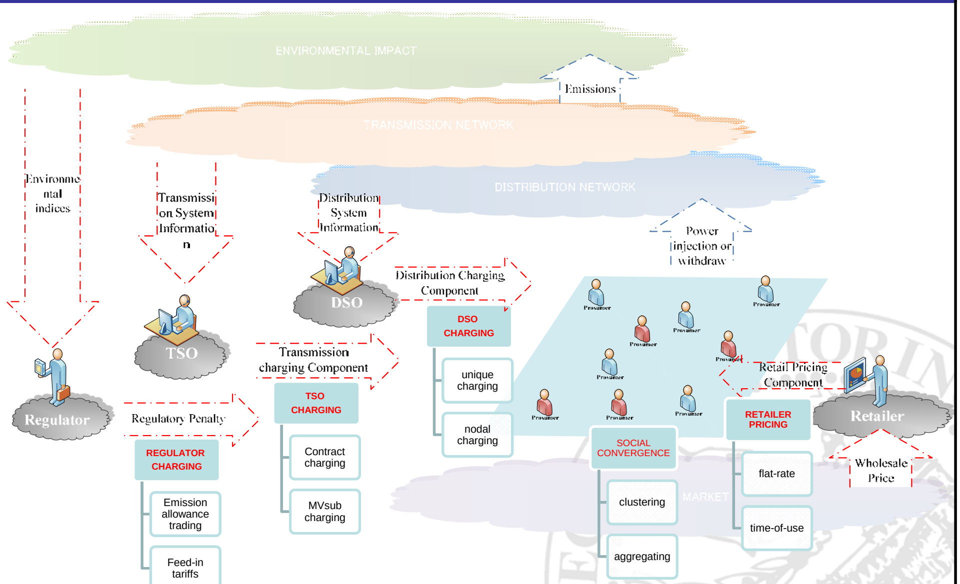


Whole Market Pricing Scheme

- Price for prosumer to sell: $\rho = \rho_1 + \rho_2 + \rho_3 + \rho_4$
- Price for prosumer to buy: $v = v_1 + v_2 + v_3 + v_4$

- $\rho_1\, v_1$ (energy production price) : are set by the retailer fixed or based on 24 hour (time of use); charging due to balancing issue
- $\rho_2\, v_2$ (transportation / net charges) : belong to DSO, Keep the LV/MV SG feasible (within voltage and line flow limits); Reduce loss? Keep quality of service? Keep load/gen balanced?
- $\rho_3\, v_3$ (local balance price) : pricing signal to balance the local generation and demand towards an objective power value expected from upper level grid.
- $\rho_4\, v_4$ (emission cost) : a pricing component coming from emission trading and market.

Pricing schemes and interactions



CONCLUSIONS

- EES are complex multilayers systems and need proper modeling/simulation tools.
- The focus need to be shifted from “inside layers” to the interconnecting variables among different layers.
- Different expertize from various areas (traditionally far) such as sociology, phycology, electrical engineering, ICT, economics, policy making need to be pooled together.
- The tools that can be derived might be very useful for getting the best global performance in a context of distributed decision maker with conflicting goals and interests
- “Understand complexity to rule the system”