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All4green

Lakeside Research Days 2012

An Example of a Demand-Response System in the Smart Grid

Hermann de Meer, Andreas Berl, Richard Holzer,
and Michael Beck

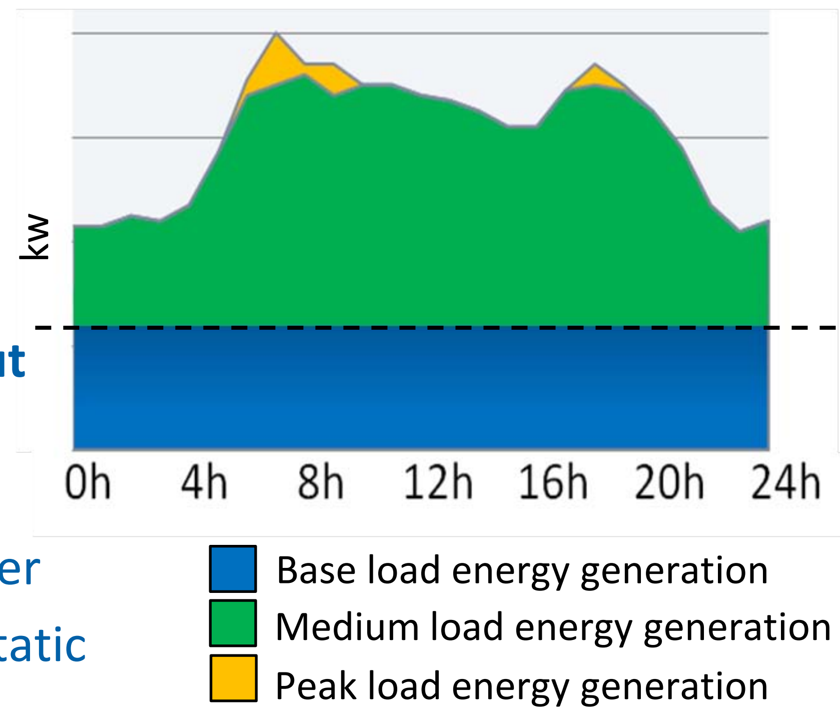
Project partners:

Grupo Corporativo GFI Informática, HP Italiana, University of Passau, Stadtwerke Passau GmbH, :a:k:t: Informationssysteme AG, University of Mannheim, Almende B.V., Universitat Politècnica de Catalunya, Wind Telecomunicazioni

Computer Networks
& Communications
Prof. Hermann de Meer

Power grid challenges

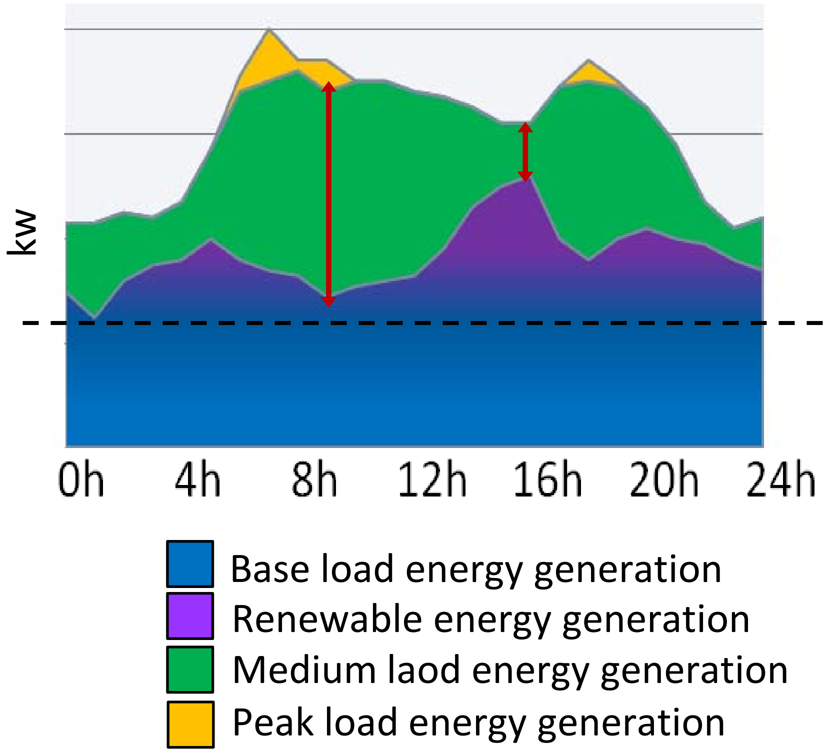
- The grid needs to be maintained in a **stable state** at all times
  - Production needs to closely meet the demand of energy
  - Very narrow tolerance
  - Unstable grid may lead to **blackout**



- **Problem 1: Peaks in energy demand**
  - Currently solved by energy provider
    - Demand prediction by using static energy consumption profiles
    - Energy provider must react to unforeseen changes
    - ➔ Peak load energy generation

Power grid challenges

- **Problem 2: Volatility of renewable energy production**
  - More and more renewable energy is fed into the power grid
    - E.g., solar power is fed in by energy customers
    - Subsidies for photovoltaic based energy production
  - Production/demand prediction becomes a difficult problem
  - Renewable energy is even meant to partly replace base energy generation (nuclear power plants)



Reshaping energy demand

- Reshape of energy demand to **flatten peaks** in energy consumption
  - Peaks may be caused by
    - Special events (e.g., football match)
    - A sudden drop of renewable energy (e.g., clouds, no wind)
    - Weather conditions (heating in winter, air-conditioning in summer)
  - Peaks in energy demand may **destabilize** the grid!
    - **Pay** neighbouring countries to get energy delivered
      - Buying nuclear energy
    - Emergency plan needed
      - What can be turned off to prevent a blackout?
      - University? Hospital?

Reshaping energy demand

- Reshape of energy demand to **consume a surplus** of renewable energy
  - Surplus may be caused by
    - Sudden increase of renewable energy (e.g., no clouds, wind)
    - Nobody needs available energy
      - E.g., on Sundays, holidays, when people are not working
  - Surplus of energy may also **destabilize** the grid!
  - Current solutions
    - Turn off regenerative power plants (> 100 kWp)
    - **Pay** neighbouring countries to take the surplus of energy
      - Allgäuer Überlandwerk paid Austria 15 times during 2011
        - Expected for 2012: about 50 times
        - Buy energy back during the night (**pay twice**)

Reshaping energy demand of data centers

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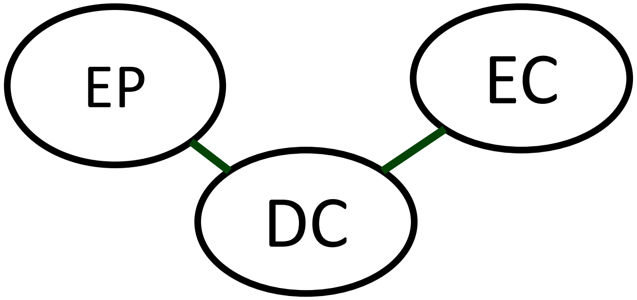
- Data centers are significant consumers of energy
  - "The European data center consumption was 50 terawatt hours (TWh) in 2008. This will rise to 100 TWh by 2020, roughly the same as the electricity consumption of Portugal."
    (Source: http://www.guardian.co.uk/sustainable-business/data-centers-energy-efficient)
- Data center energy management technology today
  - Methods to reduce the data center's energy consumption
- Novel approach: EU project All4green
  - Considers the ecosystem of the data center
    - Energy provider – data center – customer
  - Flexible adaption of data center's energy demand

Data center eco-system

- Energy provider (EP)
  - Knows and manages energy production and the grid's load situation
  - Creates new green tariffs to motivate data centers to become flexible
- Data center (DC)
  - Reduces its energy consumption
  - Reacts in a flexible way to changing load situations in the grid
- End customer (EC)
  - Green Service Level Agreements (SLAs) include the end-customer in the green energy management
  - The QoS may temporarily be reduced for the customer



Eco-system

Data center eco-system

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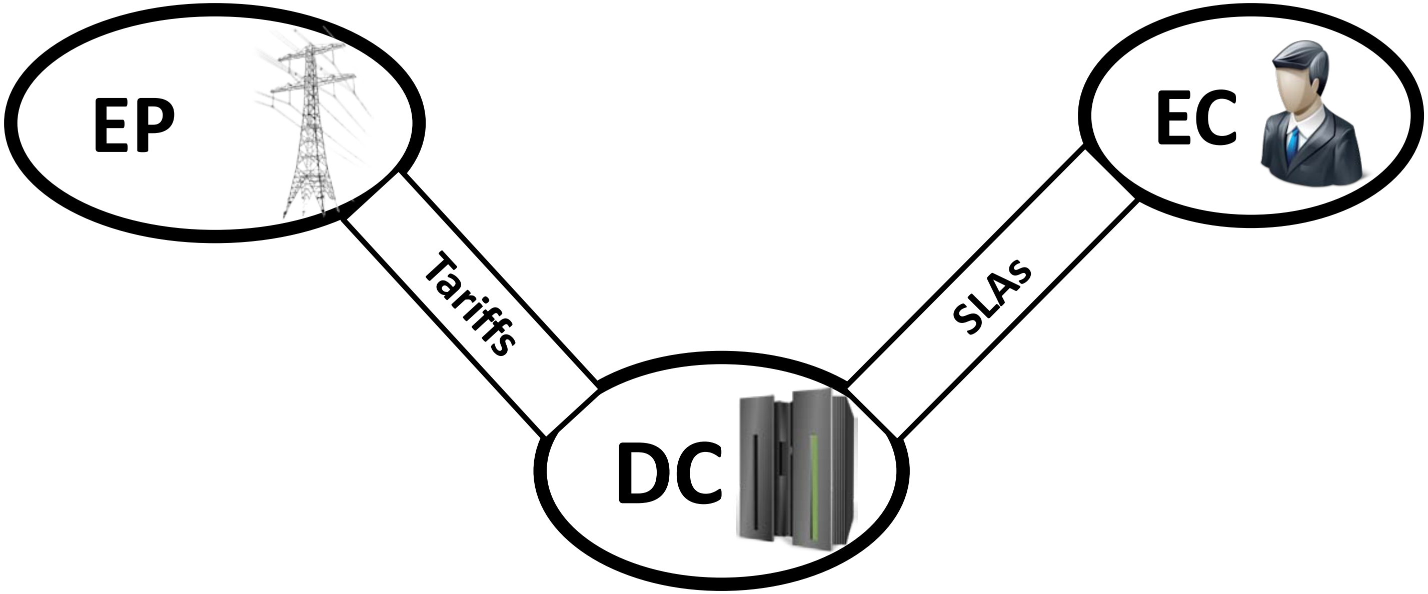

Data center eco-system

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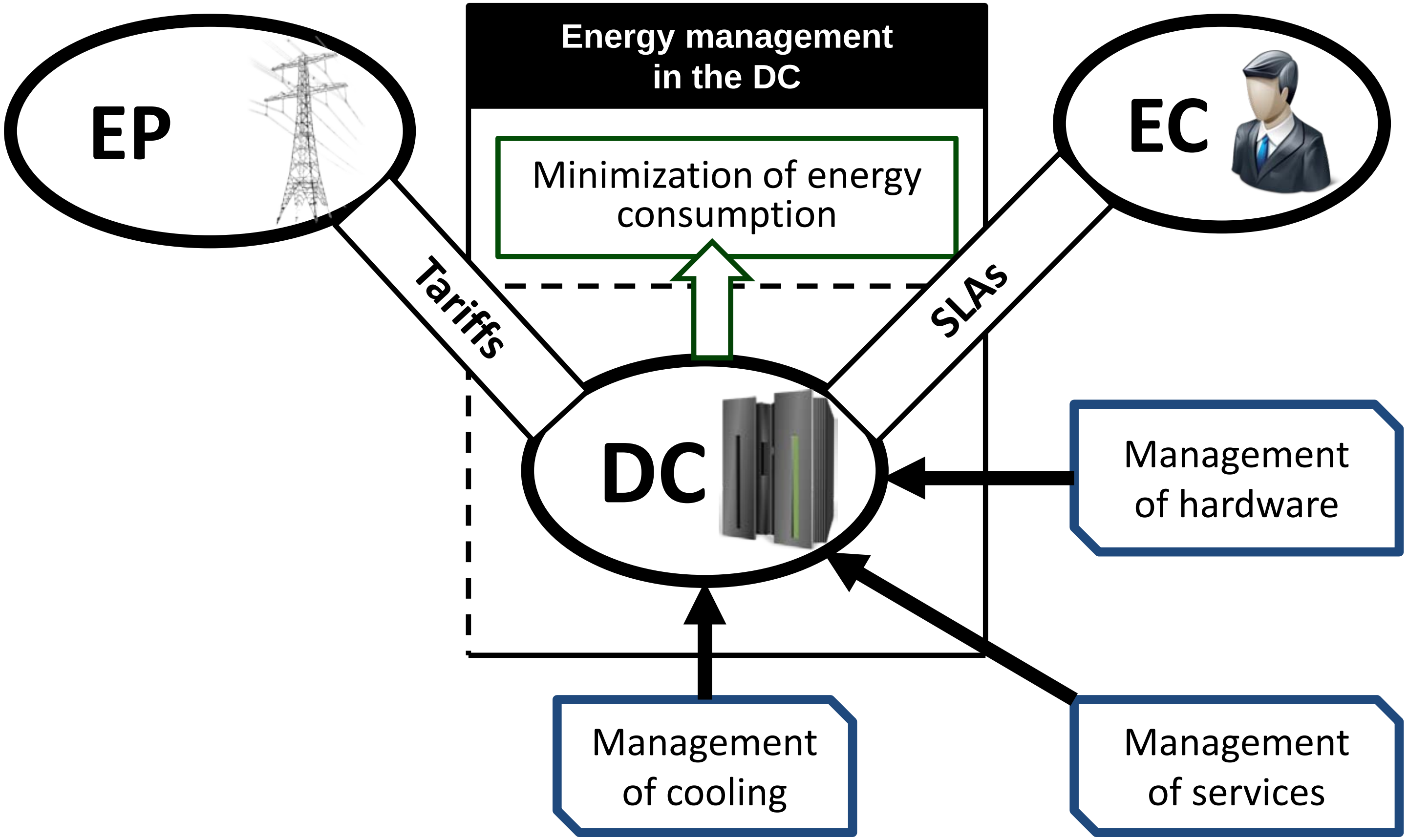
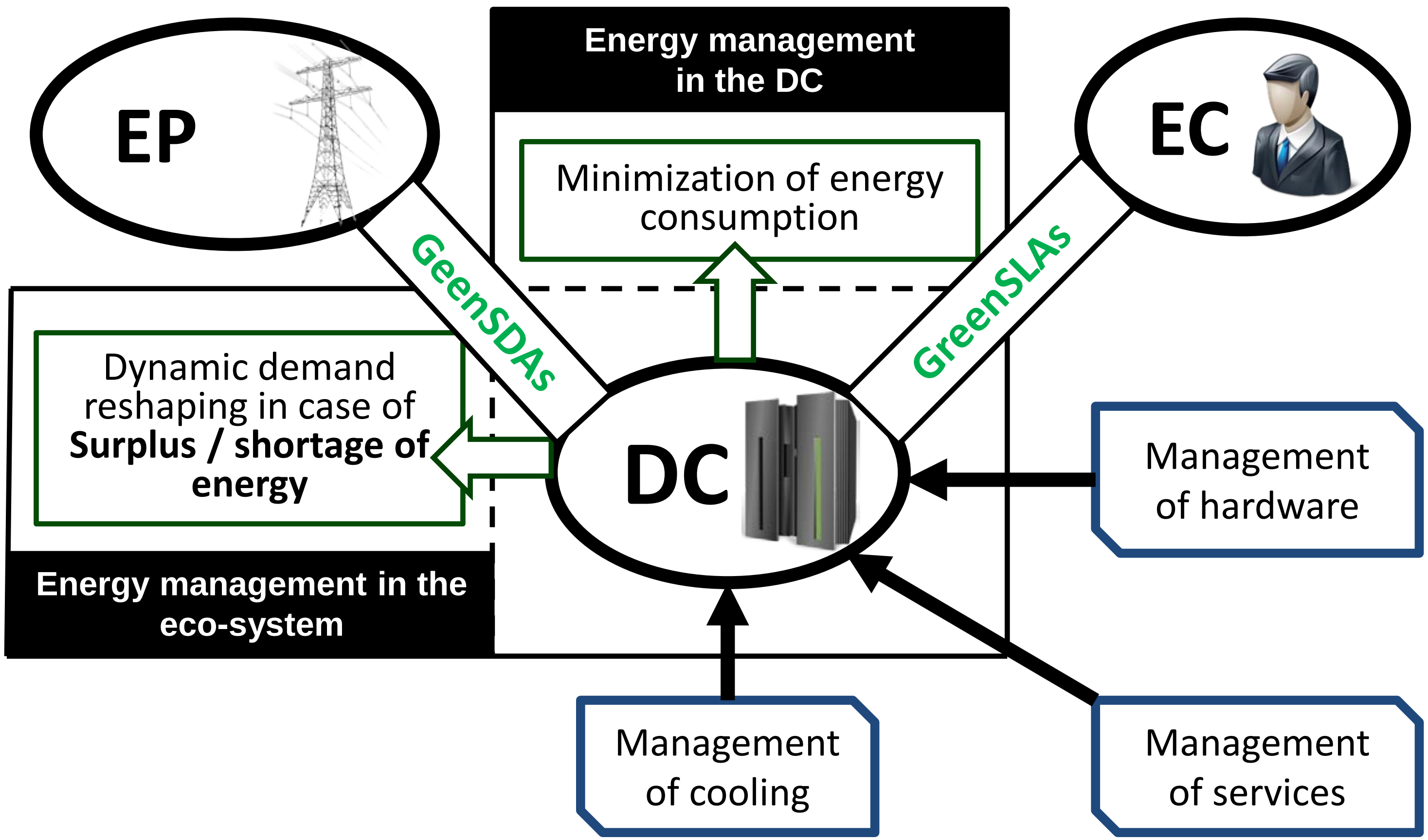


Data center eco-system



Flexibility in the data center

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All4green	Adaption of energy demand	Shifting of energy demand
Management of services	Consolidation of services	
Management of hardware	Enable energy-saving features	
Management of cooling	Increase basis temperature	

Flexibility in the data center

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All4green	Adaption of energy demand	Shifting of energy demand
Management of services	Consolidation of services / Deconsolidation of services	Postpone services / Prepone services
Management of hardware	Enable energy-saving features / Turn hardware to maximum performance	Run devices on UPS and diesel generators / Charge UPS
Management of cooling	Increase basis temperature / Decrease basis temperature	Deactivate cooling temporarily / Proactively cool down to lower temperature

GreenSDA:
Green Supply/Demand Agreement

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- More than traditional tariffs
  - Energy provider agrees to supply energy
  - Energy customer agrees to be flexible in demand
- Offer incentives in exchange for flexibility in energy demand
  - Lower energy prices, bonuses
  - Flexibility is paid, similar to booking a seat at an airline
- **Green SDA Example:** Data center agrees to reduce/increase energy consumption if requested by the energy provider
  - by **X** kWh
  - for at least **Y** minutes
  - **Z** times a year (maximum)
  - Data center is allowed to deny a request **W** times

GreenSLA: Green Service Level Agreement

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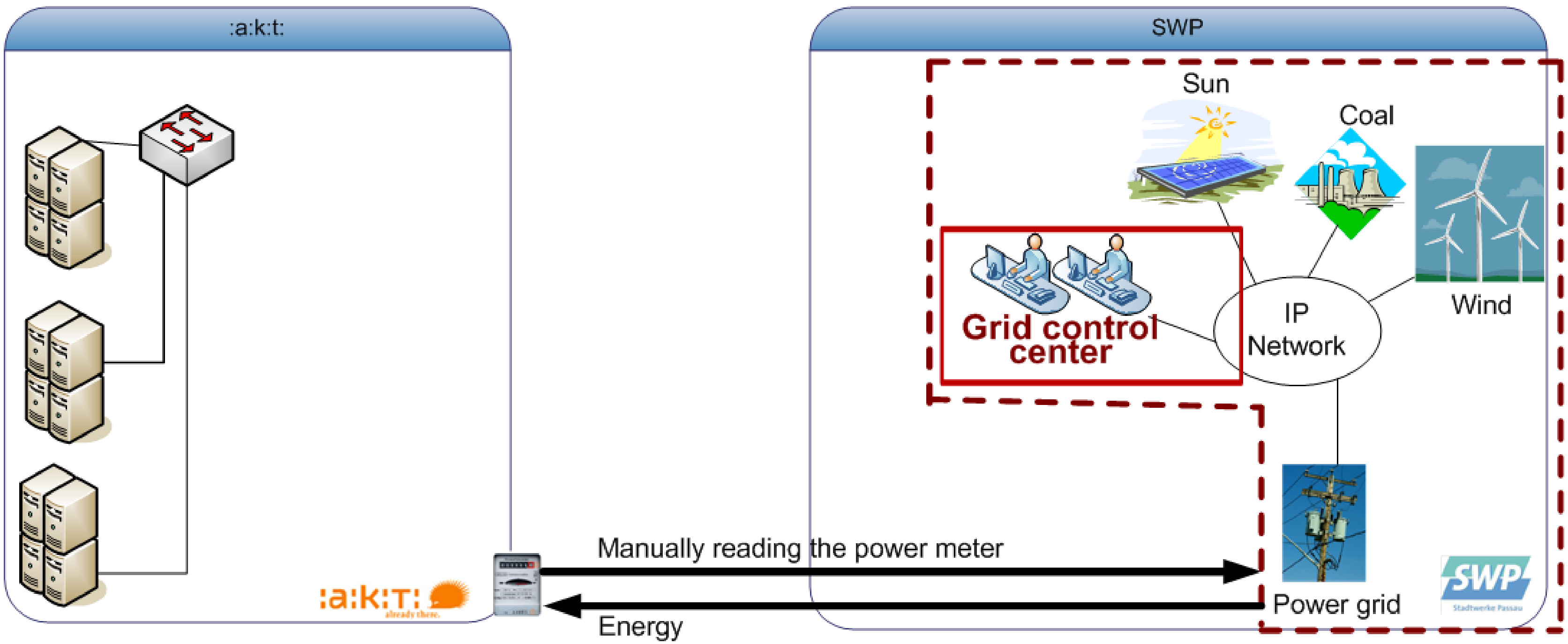
- Relax traditional performance parameters
  - Delay, jitter, response time
- Introduce energy performance parameters
  - E.g., variant response time
- Offer incentives in exchange for a specified variation of traditional performance metrics
  - "Green services"
  - Reduced cost of service
- **Green SLA Example:** IT end user accepts …
  - reduced QoS at night
  - or slightly varying QoS during daytime
  - or even limited downtime of the service if announced beforehand

Testbed in Passau

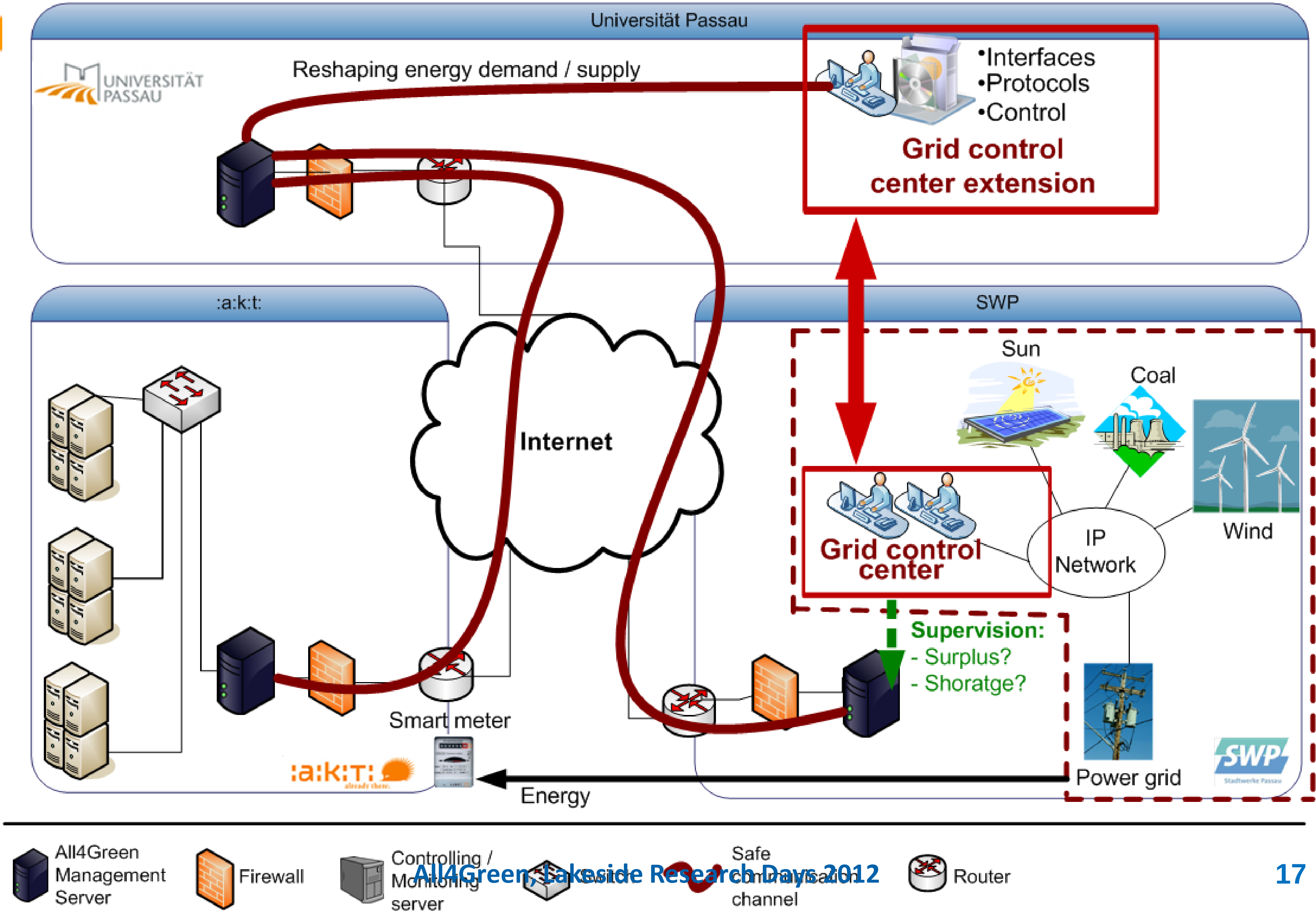
- University of Passau
  - Development of an energy management system
    - Energy provider – data center/households/…
  - Modeling of communication, signaling
  - Development of energy adaption/shifting management for data centers
- Stadtwerke Passau GmbH
  - Energy provider for Passau and surroundings
  - Provides infrastructure, information, new tariffs
- :a:k:t: Informationssysteme AG
  - SME with about 120 employees
  - Provides data center and helps in developing mechanisms and management within the data center; develops green SLAs

Situation before the project

- No direct communication between energy provider and data center
  - Data on energy consumption only gathered for accounting



Testbed in Passau



Quantitative Measures

How can we measure self-organizing properties in Smart Grids?

- For building a **self-organizing Smart Grid**, we first we have to identify, which properties we want to achieve.
- In the recent years, **quantitative measures** have been defined to measure self-organizing properties of complex systems.
- These measures can be used for the **design** and **implementation** of self-organizing Smart Grids and for the **optimization** of system parameters with respect to specified goals.

Quantitative Measures

Quantitative measures based on information entropy H

- Levels of **emergence**
  - Are there any coherent patterns induced by local interactions?
- Levels of **autonomy**
  - How much control data from external entities are needed to keep the system running?
- Levels of **global state awareness**
  - How much information does a single entity have about the global state (averaged over all entities)?

Quantitative Measures

Quantitative measures based on fitness functions

- Levels of **target orientation**
  - Is the high-level goal that the system designer had in his mind, reached by the system?
- Levels of **adaptivity**
  - Is the high-level goal also reached after changes in the environment (new control data from external entities)?
- Levels of **resilience**
  - Is the high-level goal still reached after unexpected events in the system (e.g. break down of nodes, attacks by an intruder, …)?

Although quantitative measures are defined analytically on micro level, it is usually too difficult to calculate them analytically, so they are approximated by simulations.

Self-organization in the Smart Grid

Self-organizing properties in the Smart Grid Scenario (1)

- Autonomy
  - Can all decisions be made autonomously by the entities?
    - Price adjustment
    - Activation/deactivation of energy consuming devices
- Adaptivity
  - Can the entities automatically adapt to changes in the environment (e.g. grave changes in the overall energy consumption)?
- Emergence
  - Are there any emerging global patterns resulting from the interactions between the entities?
    - Stability or oscillating patterns in energy consumption and/or price?

Self-organizing properties in the Smart Grid Scenario (2)

- Resilience
  - How resilient is the system with respect to unexpected events?
    - Failures in the system
    - Attacks or misbehavior of users
- Global state awareness
  - Is the knowledge of a single entity about the whole system state enough to make the right decisions?
- Target orientation
  - Are the overall goals satisfied by the system?

Conclusions – All4Green benefits

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- Energy provider
  - Saves money : Shifts from fossil based energy generation to renewable energy generation and avoids peak energy production
  - Keep grid stable
    - Emergency plan: Communication with mayor energy consumers is enabled : Tell them to reduce their consumption before blackout
- Data center
  - New business model: can provide “green services” to customers
  - Saves energy
  - Saves money through new energy tariffs
- Customer of data center
  - Is able to use (possibly cheaper) “green services”

Appendix

Micro-Level Modeling

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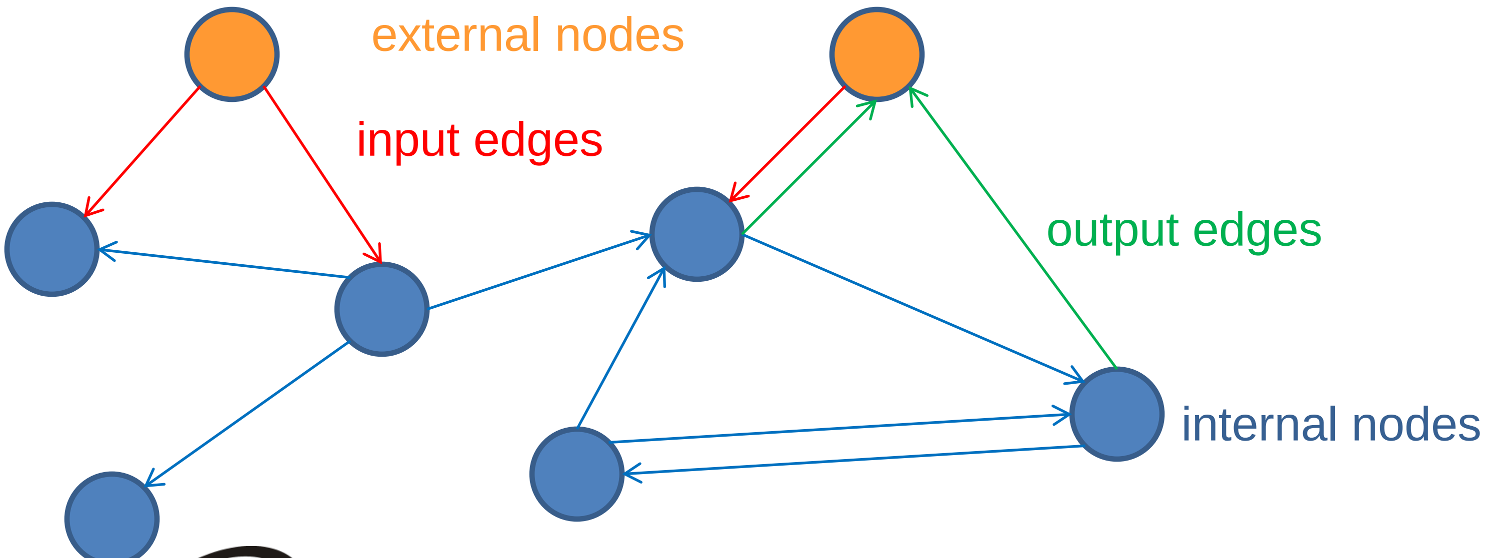
- **Topology** can be described by a **directed graph G = (V, K)**
- **Behavior** can be described by local rules (e.g. stochastic automata) for each node.
- **Environment** can be described by external nodes in the graph.



From Micro-level to Macro-level: Quantitative Measures

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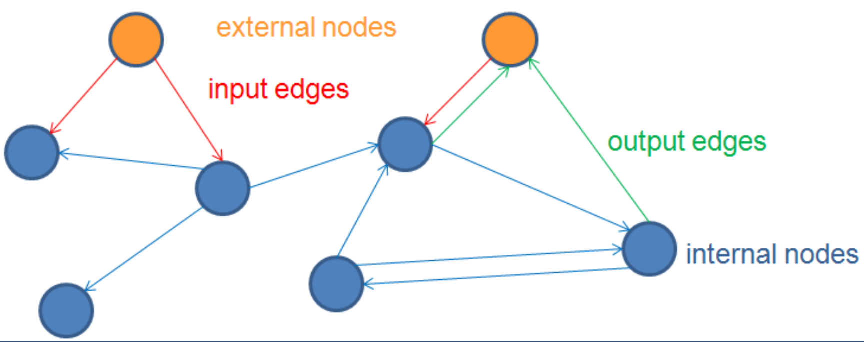
To measure **self-organizing properties** of a system, we need to determine the quantity of information in the system.

Statistical **Entropy** of a random variable X:

$H(X) = - \sum P(X=w) \log_2 P(X=w)$

With this concept we can measure for each point of time

- the information in the **whole system**
- the information on the **internal edges**
- the information on the **input edges**
- the information on the **output edges**



Emergence

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To measure the **level of emergence**

$\varepsilon \in [0, 1]$

of a system, we consider the values in the communication channels $k \in K$ between the entities and compute the dependencies.

At time t we compare the information contained in all channels with the sum of the information contained in each single channel:

$$\varepsilon_t = 1 - (H(Conf_t|_K) / \sum_{k \in K} H(Conf_t|_k))$$

where $Conf_t$ is the **global state** containing all local states and all values on the communication channels at time t and $Conf_t|_K$ is the valuation of **communication channels** at time t and H denotes the information entropy.

Level of emergence of the whole system in the interval [0, T]:

$\varepsilon_{[0, T]} = Avg(\varepsilon_t)$, Time average value of the map $\varepsilon : [0, T] \to [0, 1]$

$\varepsilon_{[0, T]} \approx 1$	**high level** of emergence	(many dependencies)
$\varepsilon_{[0, T]} \approx 0$	**low level** of emergence	(few dependencies)

Global state awareness

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To measure the **level of global state awareness**

$\omega \in [0, 1]$

the initial states are partitioned according to the equivalence relation induced by a property of interest.

Measurement of the information of each node about the **initial equivalence class** L:

For each node v:

$$\omega_{t,v} = 1 - \frac{H(L \mid \text{local history of node } v \text{ up to time } t)}{H(L)}$$

where the **conditional entropy** is defined by H(L|Y) := H(L, Y) – H(Y).

Averaging over the nodes: $\omega_t = \frac{1}{|V|} \sum_{v \in V} \omega_{t,v}$

ω_t is a **nondecreasing** function of the time:
Increasing local history leads to a decreasing entropy.

Global state awareness

Level of global state awareness of the whole system in a time interval [0, T]:

$\omega_{[0,\ T]} = \text{Avg}(\omega_t)$ Time average value of the map $\omega : [0, T] \to [0, 1]$

$\omega_{[0,\ T]} \approx 1$ means **high level** of global state awareness

(each node knows much about initial equivalence class)

$\omega_{[0,\ T]} \approx 0$ means **low level** of global state awareness

(each node knows few about initial equivalence class)

Target orientation

Before a new system is designed, we have a goal of the system in our mind:

The system should fulfil a given purpose.

Fitness function: In the model, the goal can be described by a valuation of configurations (either time dependent or time independent):

b_t : Conf ! [0, 1] (Conf is the set of all global states)

Level of target orientation at time t:

$TO_t = \boldsymbol{E}(b_t(Conf_t))$, where $\boldsymbol{E}(X)$ is the mean value of a random variable X, i.e. TO_t is the average valuation of the global state $Conf_t$ at time t.

Level of target orientation of the whole system in a time interval [0, T]:

$TO_{[0, T]} = Avg(TO_t)$ Time average value of the map TO : $[0, T] \rightarrow [0, 1]$

$TO_{[0, T]} \approx 1$ means that the system mostly runs through many good configurations
) **high level** of target orientation

$TO_{[0, T]} \approx 0$ means that the system mostly runs through many bad configurations
) **low level** of target orientation

Resilience

There are different forms of **resilience** for systems:

- Resilience with respect to **malfunctioned** entities.
- Resilience with respect to **attacks** by an intruder, which is inside the network.
- Resilience with respect to **attacks** by an intruder, which is outside the network.
- Resilience with respect to **external influence**, which might disturb the normal behavior of some nodes.

How can we define Resilience in the model?

Resilience

Idea: Assume that the behavior of each node is specified by a (stochastic or deterministic) automaton. Replace the automatons of the malfunctioned nodes by new automatons.

If the behavior of a malfunctioned node v is not known in advance, use a parameter θ to define different possible behaviors for the new automaton.

The new goal can be described by a valuation of configurations in the modified system S_θ:

b_θ : Conf ! [0, 1]

Level of resilience at time t:

$Res_t = E(b_\theta(Conf_t))$

Level of resilience of the whole system in a time interval [0, T]:

$Res_{[0, T]} = Avg(t \mapsto Res_t)$ Time average value of the map Res : $[0, T] \to [0, 1]$

$Res_{[0, T]}$ ¼ 1 means, that the new system runs through many good configurations) high level of resilience

$Res_{[0, T]}$ ¼ 0 means, that the new system runs through many bad configurations) low level of resilience

Adaptivity

A system is adaptive, if it can fulfill its task despite of changes in the environment.

Change in the environment: Replace the automatons of of controling nodes by new automatons.

If the new behavior of a node is not known in advance, use a parameter θ to define different possible behaviors for the new automaton.

The new goal can be described by a valuation of configurations in the modified system S_θ:

b_θ : Conf ! [0, 1]

Level of adaptivity at time t:

$Ad_t = E(b_\theta(Conf_t))$

Level of adaptivity of the whole system in a time interval [0, T]:

$Ad_{[0, T]} = Avg(t \mapsto Ad_t)$ Time average value of the map Ad : $[0, T] \to [0, 1]$

$Ad_{[0, T]}$ ¼ 1 means, that the new goal is reached despite the changes in the environment (the new system runs through many good configurations)

$Ad_{[0, T]}$ ¼ 0 means, that the goal is not reached after the changes (the new system runs through many bad configurations)

Autonomy

For the **level of autonomy**

α 2 [0, 1]

of a system, we compare the information contained in the **control edges C** with the information contained in **all edges** during the whole run of the system:

$$\alpha_t = 1 - (H(\text{values on C}) / H(\text{values on K}))$$

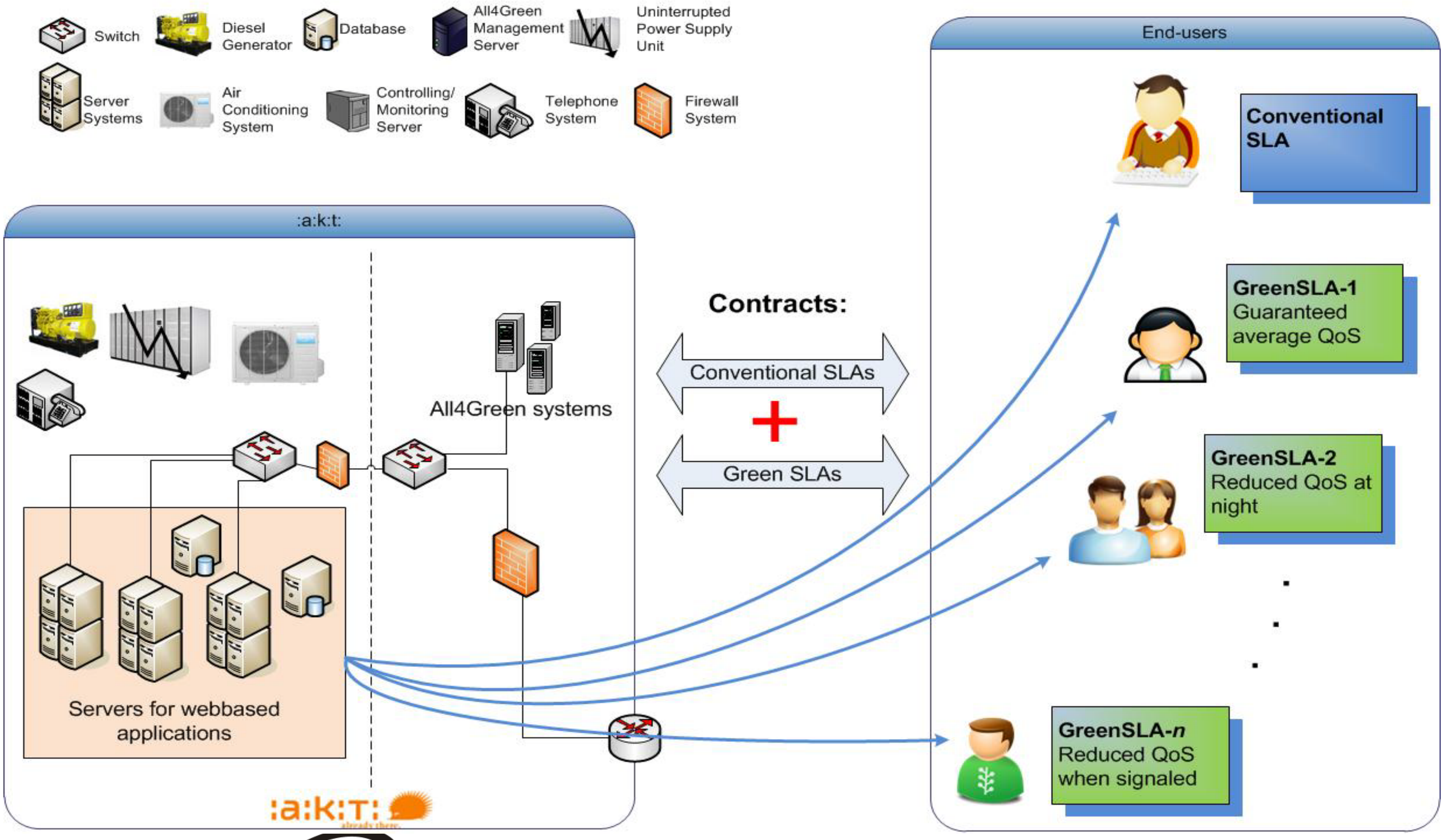
Level of autonomy of the whole system in a time interval [0, T]:

$\alpha_{[0,\, T]} = \mathrm{Avg}(t \mapsto \alpha_t)$ Time average value of the map $\alpha : [0, T] \to [0, 1]$

$\alpha_{[0,\, T]}$ ¼ 1   **high level** of autonomy   few control data

$\alpha_{[0,\, T]}$ ¼ 0   **low level** of autonomy   much control data

GreenSLAs



Switch
Diesel Generator
Database
All4Green Management Server
Uninterrupted Power Supply Unit
Server Systems
Air Conditioning System
Controlling/ Monitoring Server
Telephone System
Firewall System
:a:k:t:
All4Green systems
Servers for webbased applications
Contracts:
Conventional SLAs
Green SLAs
End-users
Conventional SLA
GreenSLA-1 Guaranteed average QoS
GreenSLA-2 Reduced QoS at night
GreenSLA-*n* Reduced QoS when signaled