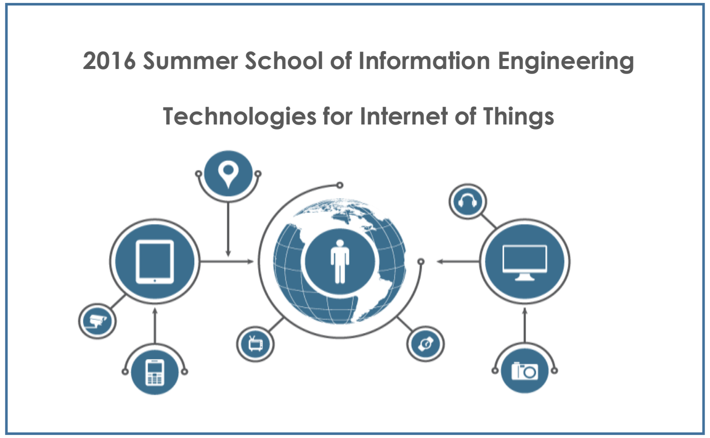
Sustainable Mobile Networks



Centre Tecnològic de Telecomunicacions de Catalunya

Paolo Dini

Senior Researcher
Communication Networks division
paolo.dini@cttc.es
http://www.cttc.es/people/pdini/

Outline

- Introduction & Motivation
  - Sustainability
  - ICT and society
  - ICT and environment
- Sustainable 5G Networks
  - SCAVENGE European Training Network
- Selected study cases
  - Communication cooperation
  - Energy cooperation

Sustainable development

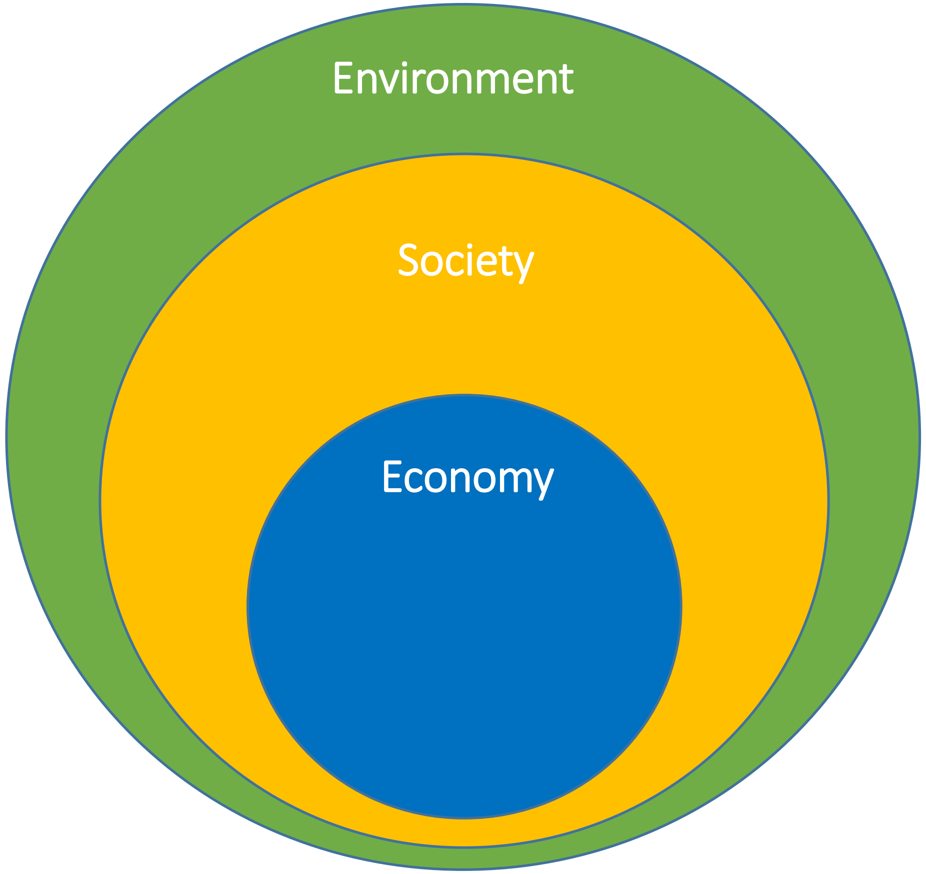
"Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs."

Brundtland definition

WCED: World Commission on Environment and Development: Our Common Future. Oxford University Press, Oxford (1987)

- Three pillar model
  - finding a balance between the environment, society, and economy

The nested model



UNESCO Engineering Initiative

- Sustainable Engineering is
  - *"the process of using resources in a way that does not compromise the environment or deplete the materials for future generations. Sustainable engineering requires an interdisciplinary approach in all aspects of engineering and it should not be designated as a sole responsibility of environmental engineering. All engineering fields should incorporate sustainability into their practice in order to improve the quality of life for all"*

  - *"sustainability and corporate responsibility are having an increasing influence on how organizations behave, operate and do business. There are many reasons why sustainability should be at the top of everyone's business agenda, not least because the continued survival of future generations depends on finding solutions to the combined issues of climate change, finding an alternative to carbon-emitting fossil fuels for energy and transport needs, and ensuring widespread access to clean water."*

Sustainable ICT

"(..) the study and practice of designing, manufacturing, using, disposing of computers, servers and associated subsystems efficiently and effectively with minimal or no impact on the environment."

Murugesan, S.: Harnessing green it: principles and practices. IT Prof. 10(1), 24–32 (2008)

- Making ICT goods and services more sustainable over their lifecycle, mainly by reducing the energy and material flows they invoke

ICT for sustainability

- Creating, enabling and encouraging sustainable patterns of production and consumption by means of ICT
- Examples
  - Travel substitution, digitalization and dematerialization
  - Smart grids, smart buildings, smart cities, …

ICT societal aspects

- ❑ Information and communication technologies (ICTs) now penetrate all parts of society
  - 6,8 billion of mobile subscribers*
    - almost as many mobile/cellular subscriptions as people in the world
  - 750 million households connected to the Internet*
    - 41% of the world's households
- ❑ New lifestyle options for individuals
- ❑ Efficiency benefits to businesses and organizations

*ITU – ICT Facts and Figures 2013

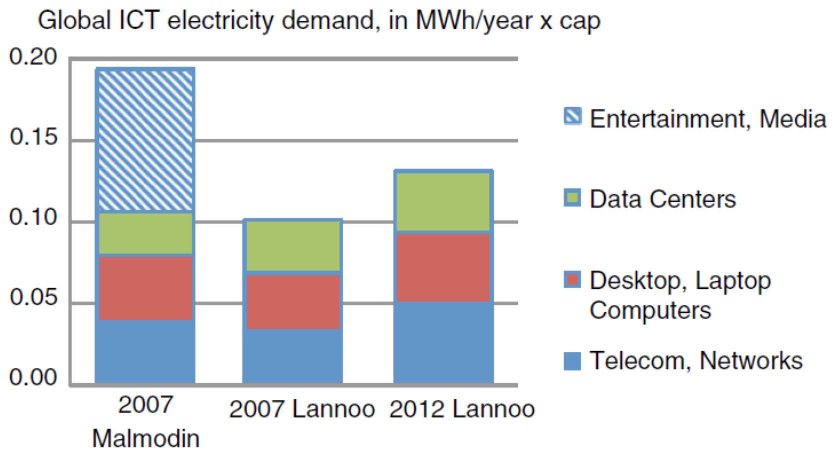
Energy demand of ICT

- The world's ICT ecosystem consumes **1500 TWh** of electric energy annually
  - 10% of the world electricity generation
  - 50% more than global aviation
  - 2-4% of carbon footprint by human activity
  - 10% of Compound Annual Grow Rate (CAGR)

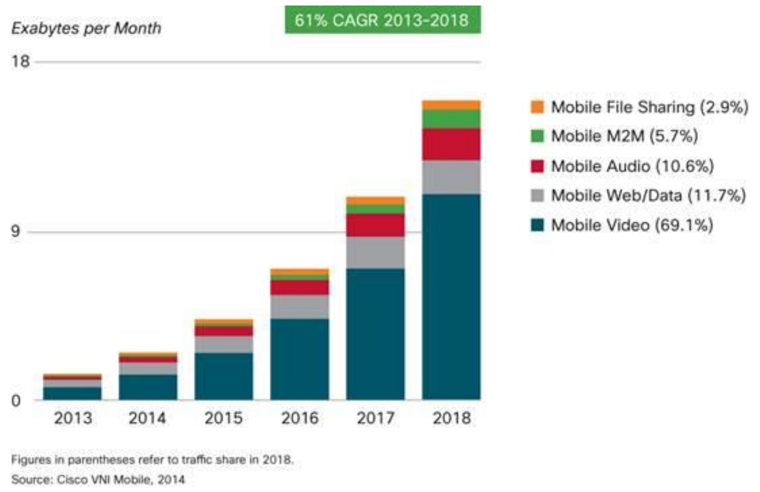
Source: Digital Power Group "The cloud begins with coal" August 2013

Source: Heddeghem et al. "Trends in worldwide ICT electricity consumption from 2007 to 2012"

- Mobile networks will have to deal with **1000x** more capacity
  - Internet of Things, Smartphones
  - Cloud applications
  - Mobile traffic annual growth rate of **70%**



Source: ICT Innovation for Sustainability, Springer 2015



The ecological perspective

- Annual increase of **11 Mto CO_2e**
  - 2020 emissions correspond to more the 1/3 of the present annual emissions of the UK
- RAN operation and production of mobile devices dominates the overall carbon footprint
- Data centres and transport experience the strongest growth

Source: Fehske et al. The global Footprint of Mobile Communications: the ecological and economic perspective, IEEE ComMag, August 2011

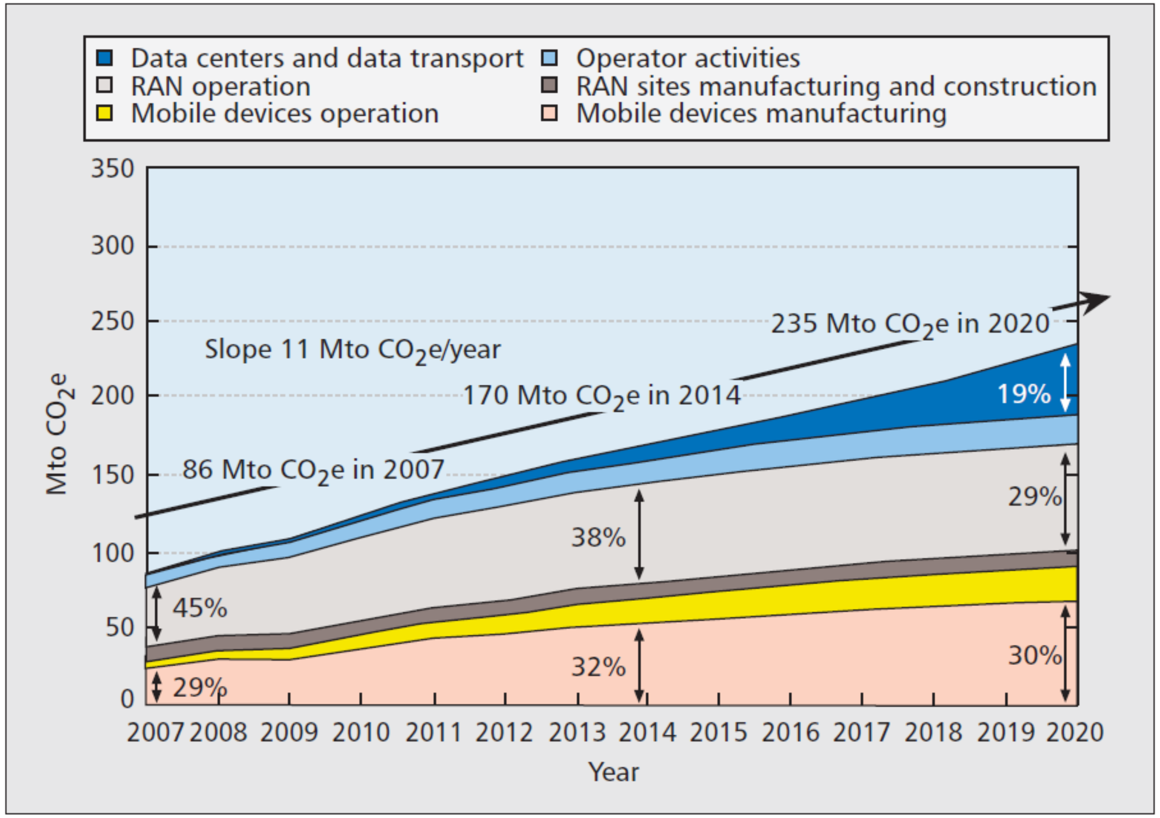


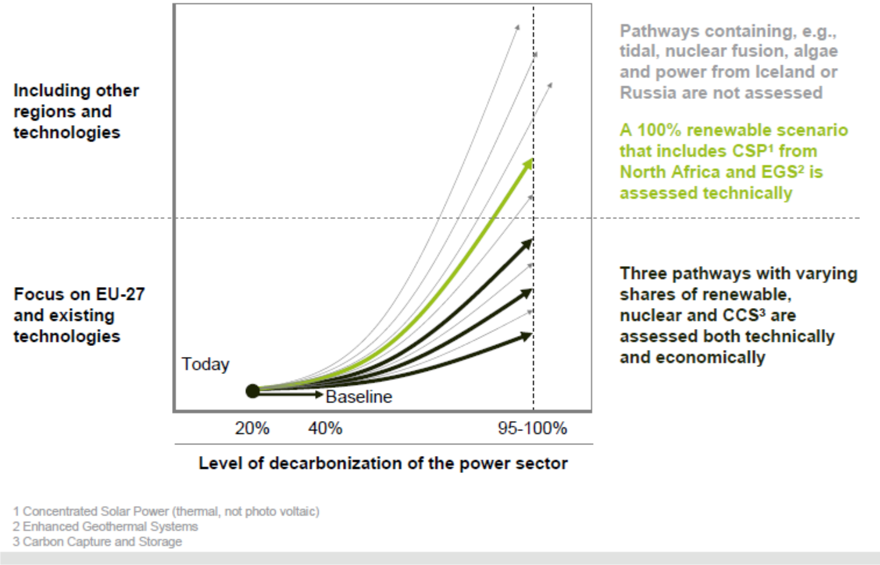
Figure 3. *Global carbon footprint of mobile communications projected until 2020.*

The economical perspective

- Energy bill due to network operations = personnel cost to run & maintain the network (western Europe 2007)
  - Increasing cost of energy
- Average Revenue Per Unit (ARPU) of mobile network operators is decreasing specially in fully penetrated markets
  - Vodafone Germany ARPU is shrinking annually by over 6% on average (period 2000 – 2009)

Political environment

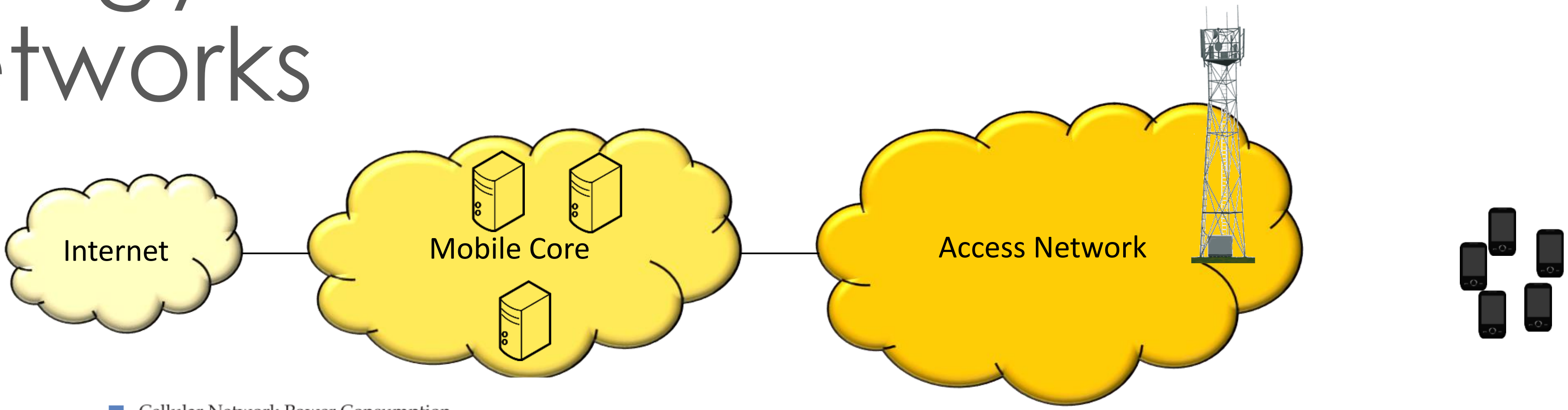
- **Roadmap 2050** (EU strategy)
  - reducing greenhouse gases (GHG) emissions **80-95%**
- Transition of the energy system in ways that would be compatible with this GHG reductions target
- Decarbonising the energy system
- Increasing the share of renewable energy and low carbon technologies

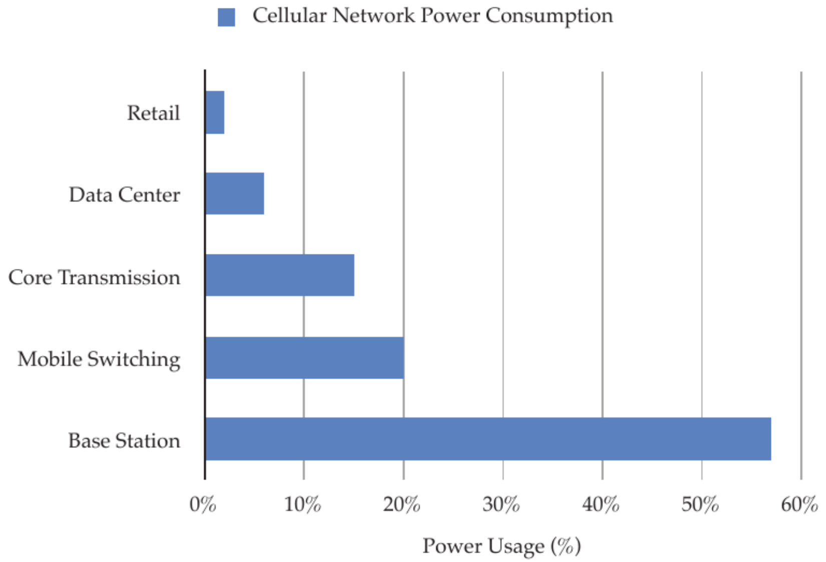


Political environment & ICT

- EU political priority for energy efficient ICT network is testified by
  - 7 Directives
  - 7 Regulatory measures
  - 5 Codes of conduct
  - 3 Studies
  - 5 Mandates
  - Support for standards
    - CEN (European Commitee for Standardization)
    - CENELEC (European Commitee for Eletrothenical Standardization)
    - ETSI (European Telecommunications Standards Institute)
      - Technical Committee on Environmental Engineering (TC EE)

Energy demand of mobile networks



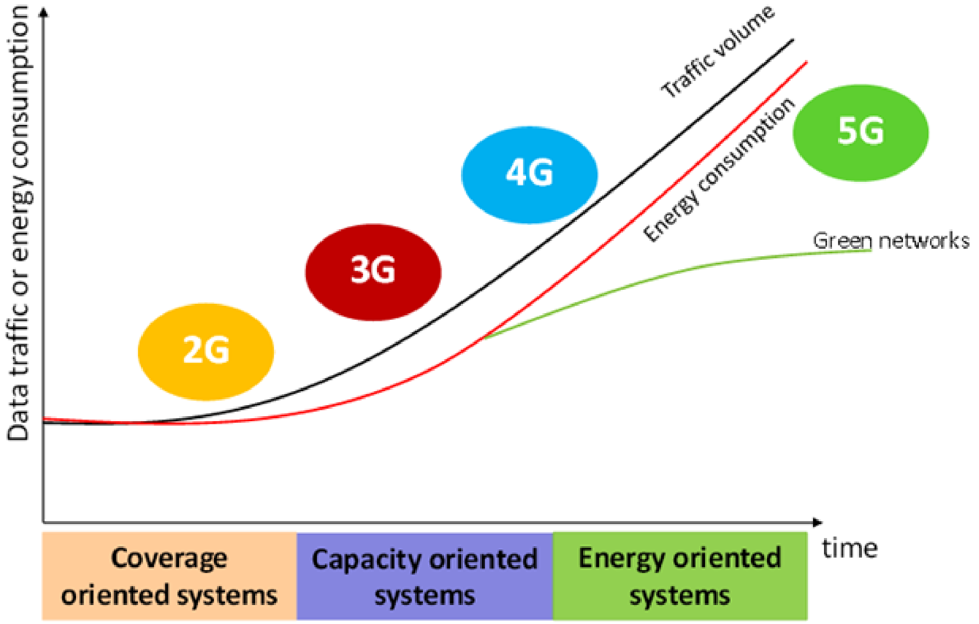


- The access part consumes the **80%**
  - mainly power amplifiers and cooling system
- BSs are used to consumes up to the 60% even when they are idle

Source: Z. Hasan, H. Boostanimehr, Vijay K. Bhargava, "Green Cellular Networks: A Survey, Some Research Issues and Challenges", IEEE Communication Survey & Tutorials , vol 13, no. 4, 2011

Energy saving

- Energy oriented systems
- Green communication & networking
  - Energy efficiency
  - Minimization of the network energy consumption
- Sustainable design principles
  - Energy harvesting
  - Renewables



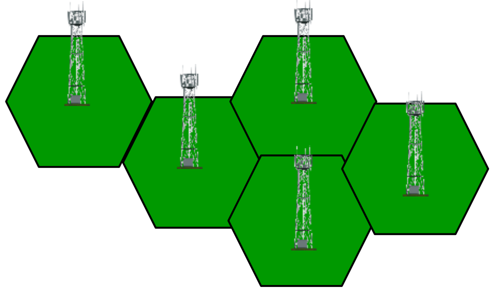
Green radio networks

- Research discipline that covers all layers of the protocol stack
- Minimizing BS energy consumption
  - Improve HW design
    - Power amplifier
    - Power saving protocols
- Energy-aware cooperative BS power management
  - Cell zooming
  - BS sleep mode
- New architectures
  - Hetnets
  - Cooperative relays

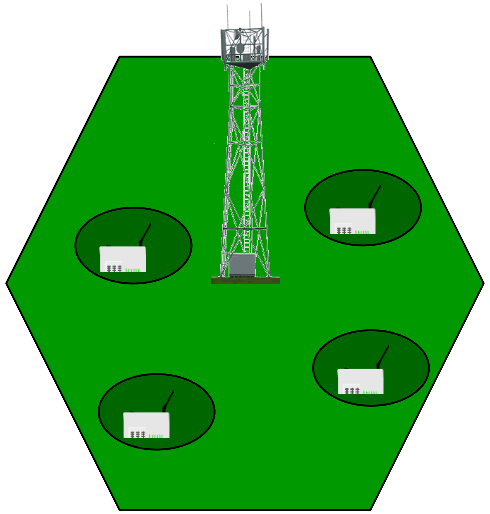
Sustainable networks

- Use of ***green energy sources and/or energy harvesters*** to supply system elements (i.e., base stations, routers, data centres, mobile devices, sensors, machines)
- *Paradigm shift* in the design of the network and devices
  - from the minimization of the network energy consumption to the maximization of network performance by using the available energy budget coming from intermittent and erratic energy sources

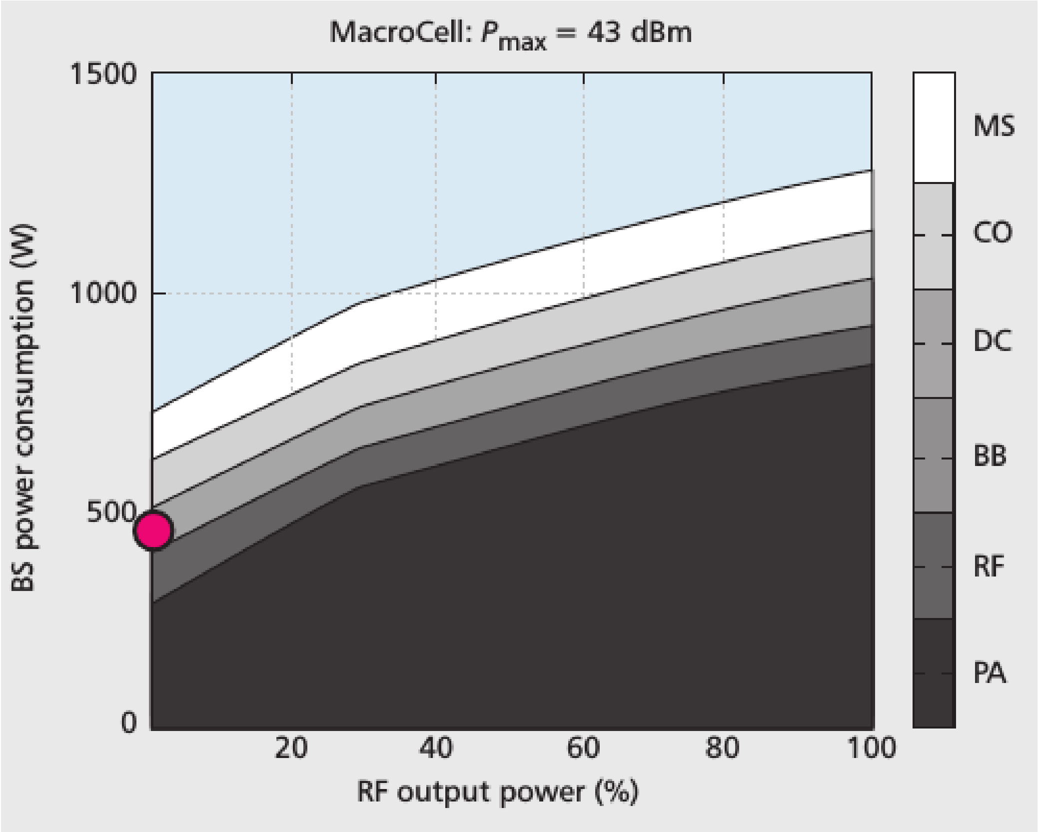
Heterogeneous cellular networks

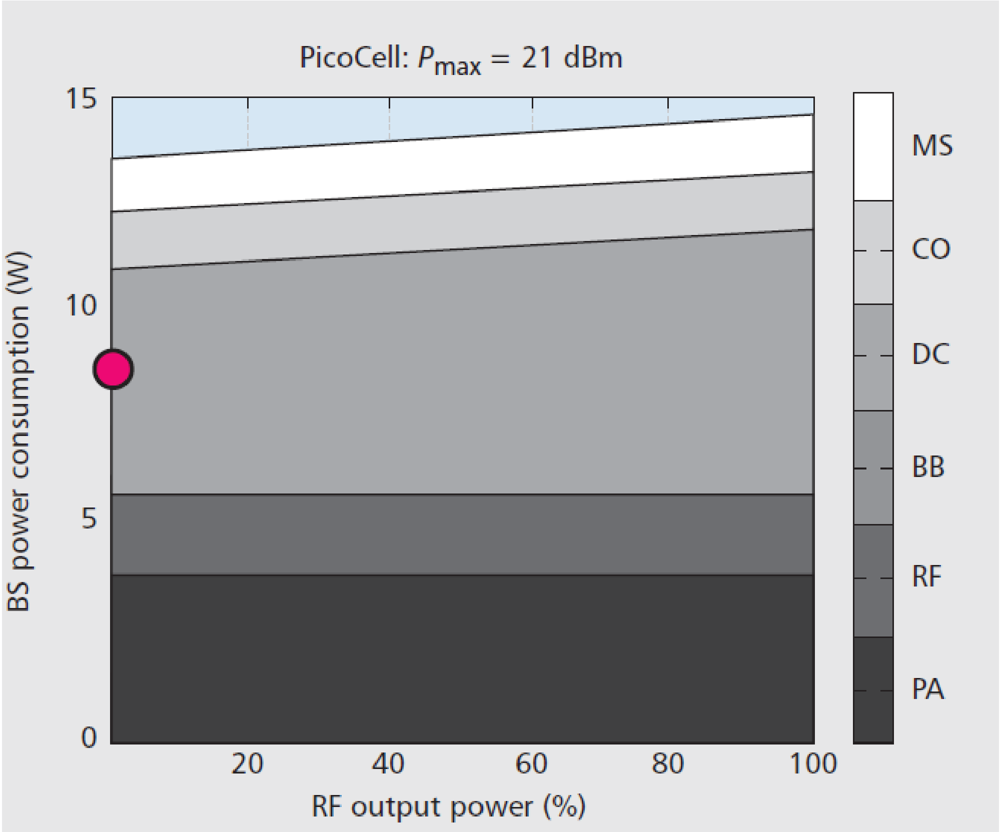


- Present architecture: macro cell deployment
- Future architecture to satisfy traffic demand
  - macro BS supported by small BSs for hot-spot capacity enhancements (HetNet, 5G)
    - High spectral efficiency
    - Installed in street furniture (no accurate planning)
    - Low energy requirements (10..100 W)



BS power consumption





SCAVENGE ETN

European Commission

Marie Skłodowska-Curie Actions

SCAVENGE

❑ Vision

- Energy sustainability is key to future mobile networks due to their foreseen capacity upsurge.
  SCAVENGE introduces the concept of Sustainable 5G Mobile Network, based on the premise that environmental energy can be scavenged through dedicated harvesting hardware, so as to power the mobile system elements like base stations, mobile terminals, sensors and machines

SCAVENGE ETN

❑ Mission

- SCAVENGE aims to create a training network for early-stage researchers (ESRs) who will contribute to the design and implementation of eco-friendly and sustainable next-generation 5G networks and become leaders in the related scientific, technological, and industrial initiatives.
  To realise its vision, the project will take a complete approach, encompassing the characterisation of intermittent and/or erratic energy sources, the development of theoretical models, and the design, optimisation and proof-of-concept implementation of core network, base stations and mobile elements as well as their integration with the smart electrical grid.

Beneficiaries

SCAVENGE

CTTC
Centre Tecnològic de Telecomunicacions de Catalunya

UNIVERSITAS STUDII PADUANI MCCXXII

Imperial College London

cea tech list

ATHONET

University of Strathclyde Glasgow

WORLD SENSING

HUAWEI

TOSHIBA
Leading Innovation

Partner organizations

NYU POLYTECHNIC SCHOOL OF ENGINEERING

A. JAMES CLARK SCHOOL OF ENGINEERING (University of Maryland)

NATIONAL INSTRUMENTS

SELTA

TELECOM SudParis

TAMPERE UNIVERSITY OF TECHNOLOGY

UNIVERSITAT POLITÈCNICA DE CATALUNYA BARCELONATECH

Expected impact

- Fill the significant skill gap in the area of ***sustainable design for ICT*** (focus on mobile networks)
  - no existing graduate program jointly covering the range of issues addressed by this ETN
- Research and training on methodologies applied to sustainable design of 5G systems for achieving an ***interdisciplinary understanding of the technology***
- ***Creation of a complete ecosystem*** of academic and non-academic partners to collaborative research in the area of sustainable design for ICT

Methodology

- Cross-disciplinary research area
  - characterization of existing energy harvesting devices, storage systems and source of energy consumption (BS, mobile devices, sensors and machines)
  - Design of network architectural functionalities (including RAN and CN protocols) and device communications conditioned on energy, channel capacity and network traffic constraints
  - Integration of the sustainable mobile networks with the smart electricity grid
- Focused individual research projects whose principal investigators are the ***14 early-stage-researchers (ESRs)***
- Training schools to complement research activities
- Enrolment in PhD programs of the universities composing the consortium

Research workpackages

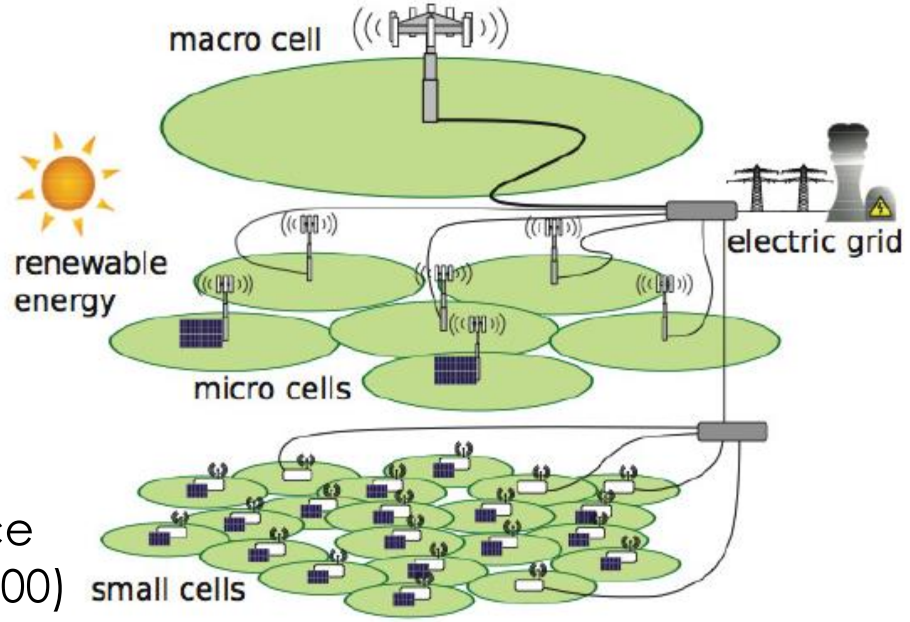
- **Energy models**
  characterization of different energy generation, storage and consumption sources composing the energy harvesting mobile system.
- **Sustainable Networking**
  design of efficient architectural framework for the management of energy harvesting 5G cellular networks to assure low overhead and topology reconfigurability.
- **Resource Optimization**
  design of the procedures and algorithms to support the predicted mobile traffic demand using the energy harvested by network elements, while assuring the best quality of experience (QoE) for mobile users and IoT applications.
- **End Device Communication**
  study of 5G network scenarios like smart cities, public protection and disaster relief (PPDR). In this context, device-to-device (D2D) communication, device-assisted networking and smart sensing from portable devices is investigated.
- **Integration with the Smart Grid**
  design of the architecture and the procedures enabling the integration of the energy harvesting cellular network with the smart electrical grid. The work is focused on new optimization paradigms, along with suitable energy trading policies and energy routing techniques to share and balance excess energy according to the prediction of traffic loads, mobility, etc.

Training program

- **Initial Training School**
  - to be held at CTTC, Castelldefels, Spain
- **School_1: 5G cellular networks and Internet of Things**
  - to be held at Imperial College, London, UK
- **School_2: Energy Generation and Storage: the case of Energy Harvesting in Mobile Networks**
  - to be held at CEA, Paris, France
- **School_3: New scenarios for 5G Mobile Networks: Smart City, Smart Grid, Public Protection and Disaster Relief**
  - to be held at University of Padova, Padova, Italy
- **School_4: Testbed Design and Prototyping**
  - to be held at Toshiba Research Europe Laboratories, Bristol, UK
- **School_5: Open Workshop on Sustainable Communications**
  - to be held at CTTC, Castelldefels, Spain

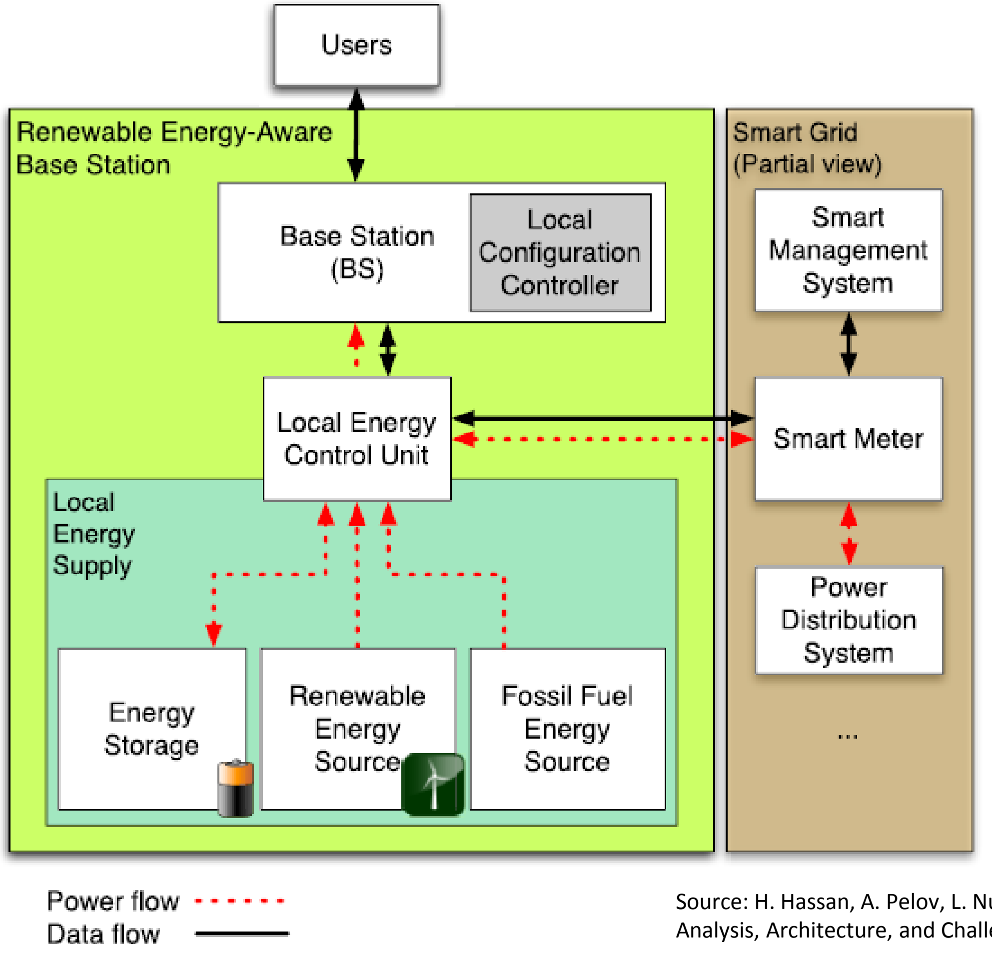
Study case

- Sustainable 5G networks (RAN & RRM)
  - Ultra-dense deployment (HetNets)
  - Integration with renewable energies
  - Scalable and lightweight architecture
  - Self-Organizing Networking (SON)
- Two main research challenges*
  - **Communication Cooperation**
    - Intermittent and erratic nature of the energy source
    - Complex system (macro and several SCs, up to 1000)
    - Solutions: traffic offloading, switch on/ff, etc.
  - **Energy Cooperation**
    - Energy trading capabilities between mobile network and smart grid (BSs as prosumers)
    - Energy cooperation between ICT and energy operators
    - Exploit energy prices dynamics



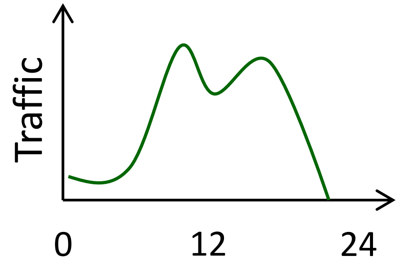
*Jie Xu; Lingjie Duan; Rui Zhang, "Cost-aware green cellular networks with energy and communication cooperation," Communications Magazine, IEEE , vol.53, no.5, pp.257,263, May 2015

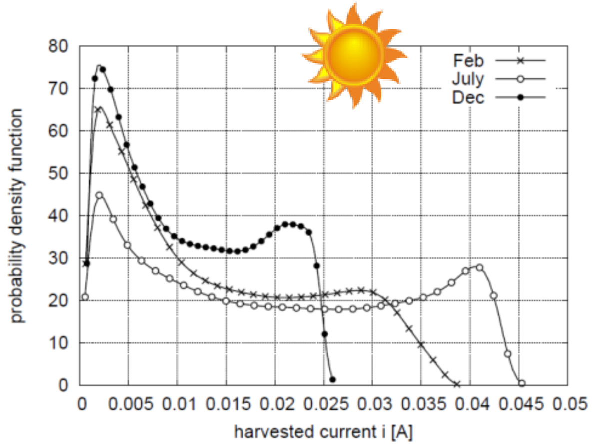
Renewable energy-aware BS



Source: H. Hassan, A. Pelov, L. Nuaymi, Integrating Cellular Networks, Smart Grid, and Renewable Energy: Analysis, Architecture, and Challenges, in IEEE Access vol.3, pg.2755-2770, 2015

Communication cooperation



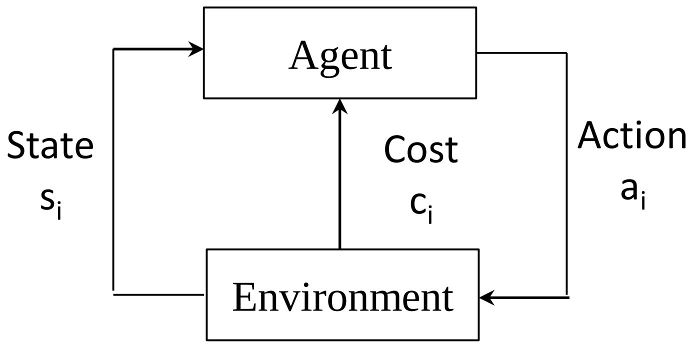


- ❑ Urban scenario – business district
  - metrocells supporting macro (1..10 W ≈ 100 m.)
- ❑ Guidelines
  - Reduce the RES system requirements
  - Adapt to the environment dynamisms (energy arrival, load)
  - Sleep part of the network when possible
- ❑ Objective
  - distributed RRM for maximizing the self-sustainability and the QoS
- ❑ Algorithm design
  - decentralized SON solution based on multi-agent reinforcement learning (RL)
  - distributed Q-Learning: each agent (SC) independently learns RRMs strategies (switch ON/OFF)

M. Miozzo, L. Giupponi, M. Rossi, P. Dini, Distributed Q-Learning for Energy Harvesting Heterogeneous Networks, in Proceedings of 2015 IEEE ICC2015

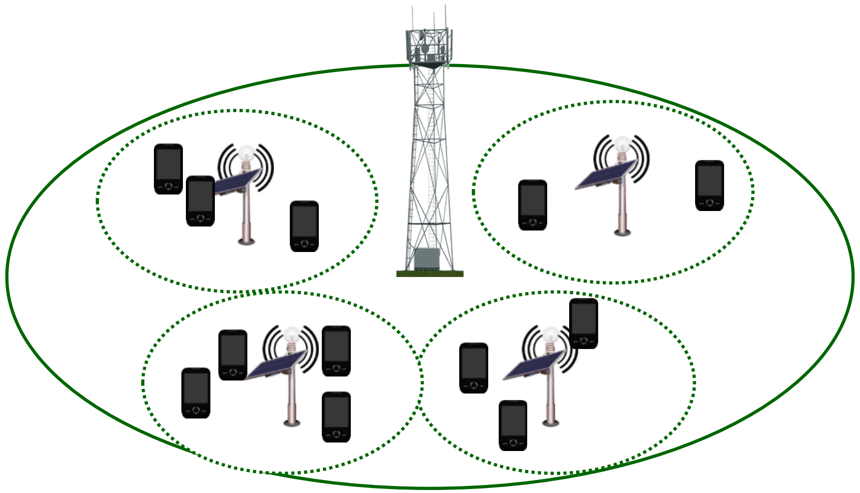
Reinforcement learning

- *"Can machines do what we (as thinking entities) can do?"* (Alan Touring)
- *"A computer program is said to learn from experience E with respect to some class of tasks T and performance measure P, if its performance at tasks in T, as measured by P, improves with experience E"* (Tom M. Mitchell)
- Reinforcement Learning
  - Ability of learning new behaviors **online and automatically** adapting to the temporal dynamics of the system
  - Environment characterized as a Markov Decision Process (MDP)
  - Set of states $\mathcal{S}$
  - Set of action $\mathcal{A}$
  - Cost function $\mathcal{C}=\mathcal{S}\times\mathcal{A}\rightarrow\Re$
  - State transition function $\mathcal{P}:\mathcal{S}\times\mathcal{A}\rightarrow\Pi(\mathcal{S})$

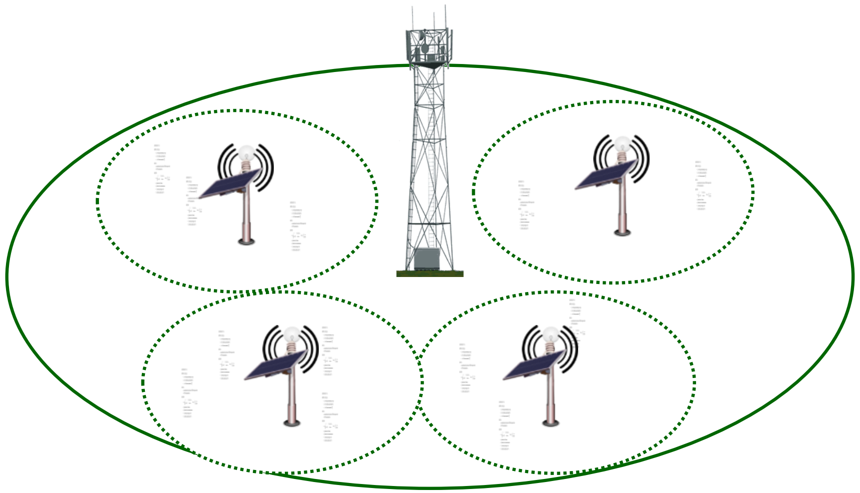


System model

- Two tiers HetNet
  - 1 macro
  - $S = |\mathcal{S}|$ SCs
  - U_s^i users in the i-th SC
- Distributed Q-learning
  - Each agent learns independently
  - Convergence to optimality not demonstrated
  - Find the optimal $Q^*(s, a)$ in a recursive manner
    - $Q(s,a) \leftarrow Q(s,a) + \Delta Q(s,a)$
    - $\Delta Q(s,a) = \alpha \left[r + \gamma \min_a Q(v,a) - Q(s,a) \right]$
      - where s and v are the states at time t and $t+1$
      - α is the learning rate



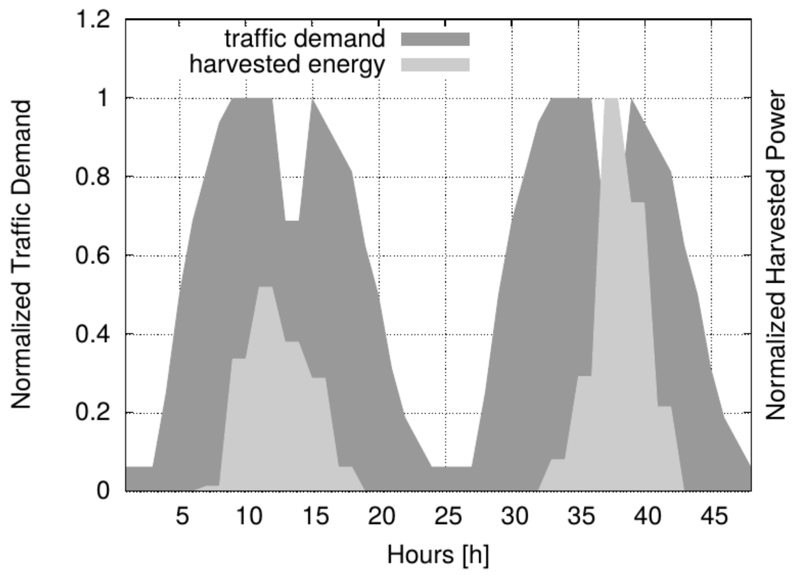
System model



- Time interval: 1 hour
- State: $s_t^i = \{E_h^i, E_b^i, L_i\}$
  - E_h^i is the energy harvested state (night vs. day)
  - E_b^i is the SC battery level quantized in E_{NUM}^{level}
  - L_i is the SC load level quantized in L_{NUM}^{level}
- Action
  - a parameter does not allow to play with SCs (8% of energy variation)
  - ON-OFF (awake/sleep) modes
- Reward
  - $r_t^i = \begin{cases} 0 & B < B_{th} \, or \, D < D_{th} \\ \frac{1-u_t^i}{B_t^i} + K u_t^i T_t^i & otherwise \end{cases}$ with $u_t^i = \begin{cases} 0 & T_t^i = 0 \\ 1 & otherwise \end{cases}$
  - B_{th} threshold on the SC battery
  - D_{th} threshold on the whole system drop rate
  - T_t^i instantaneous throughput of i^{th} SC
  - B_t^i instantaneous battery level of i^{th} SC

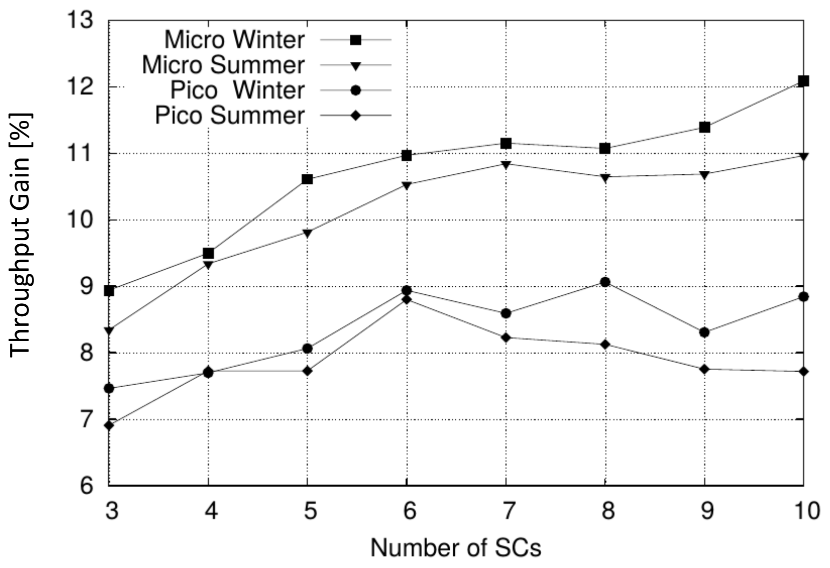
Simulation Scenario

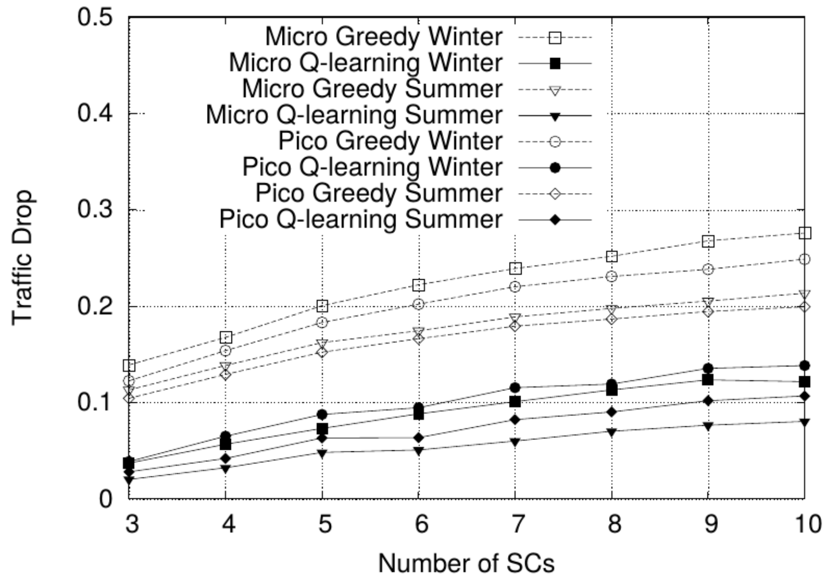
- Simulation field:1x1 km^2
  - 1 macro in the center
  - Not overlapping SCs
- Traffic profile typical business urban area
  - 120 UEs per SC
  - 20% of heavy UEs (900 MB/h) and 80% of ordinary (112.5 MB/h)
- RES system: fully recharge in 1 (good) winter day
  - Solar panel Panasonic N235B (21.1% of efficiency)
    - Micro 16x16 (4.48 m^2) and pico 6x6 (0.61 m^2)
  - Battery: Micro 2 KWh, pico 0.2 KWh
- QL: α=0.5, γ=0.9, K=10, E_{NUM}^{level} =5, L_{NUM}^{level} =3, B_{th}=0.3, D_{th}=0.03
- Exploration: ε=0.1 probability of visiting random states
- Greedy algorithm: always ON till B_{th}
- Los Angeles energy harvesting traces
- 420 days starting from January
  - 60 days of training + 360 of statistics
  - Winter: January, February, October, November, December



Throughput and Traffic Drop

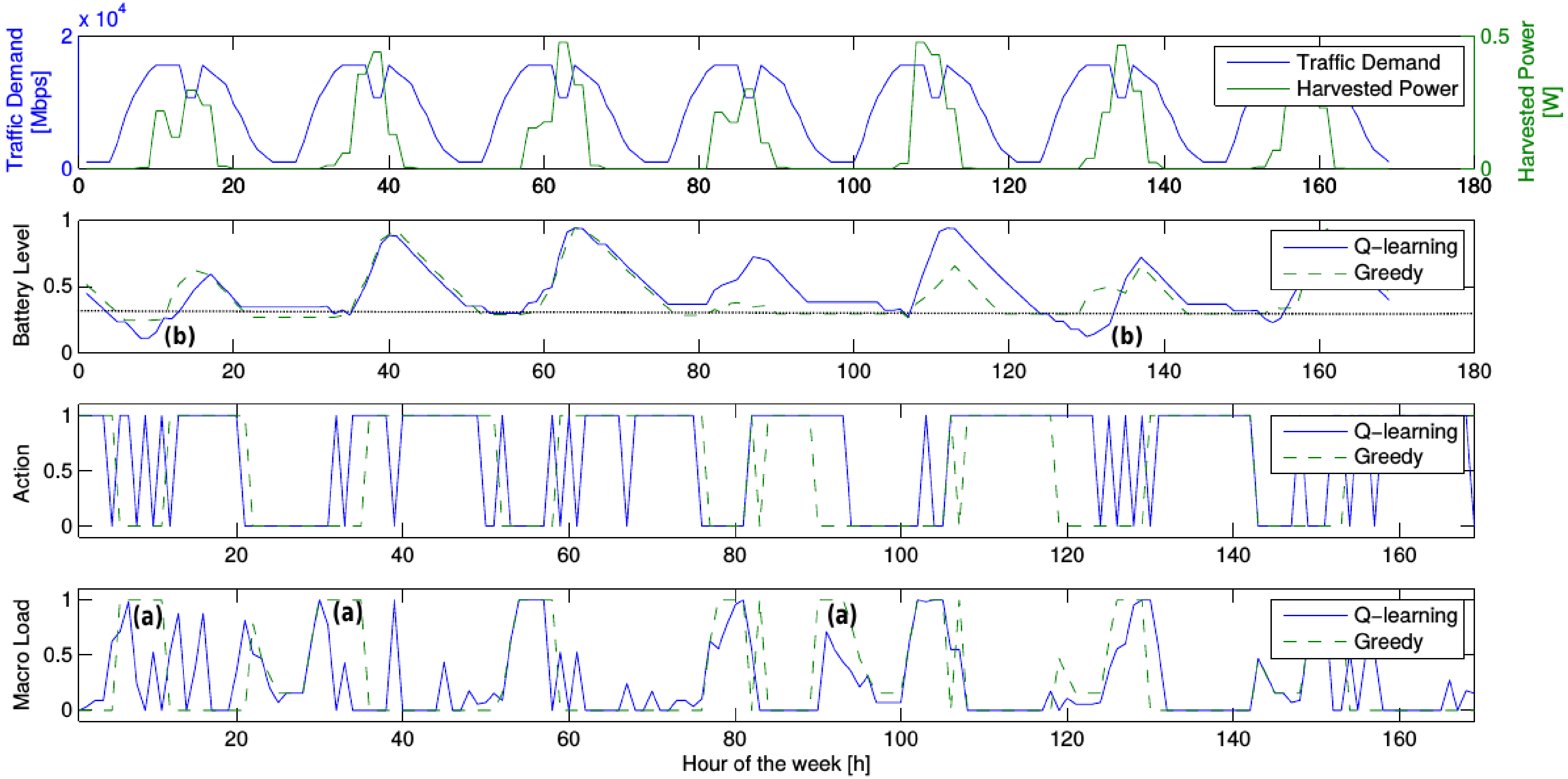
- Gain of 12% with respect to throughput
- Half of drop rate
- Micro better then pico





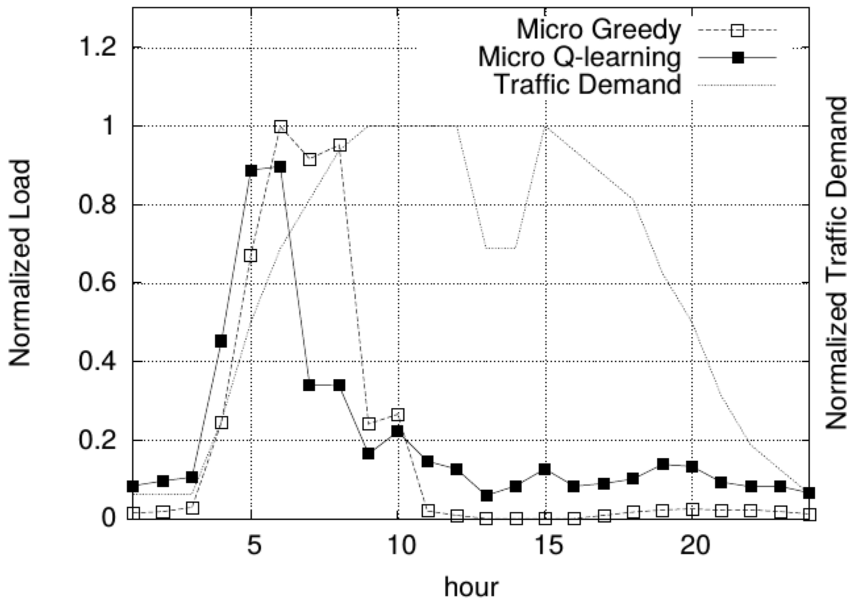
Behavior Example

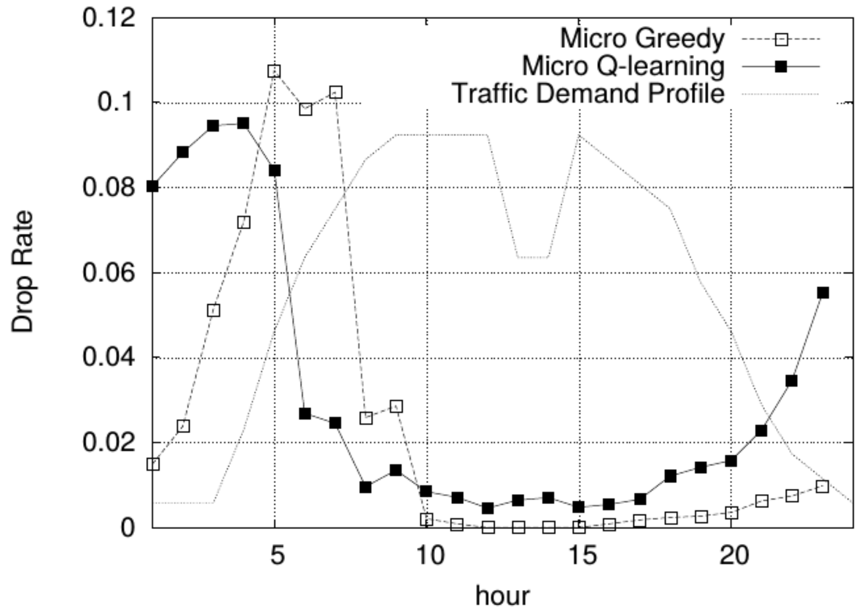
- (a) energy saving behavior during the night
- (b) QoS driven behavior during traffic peaks



Hourly Load and Drop Rate

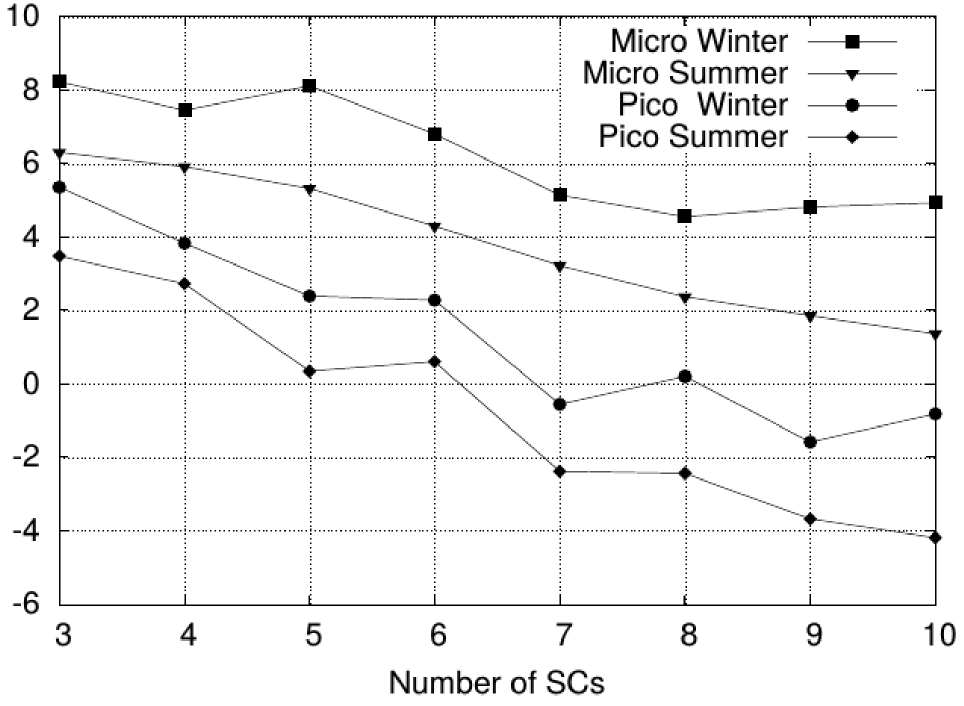
- ❑ QL spread across the day the load avoiding congestion in traffic peak
- ❑ QL has higher drop rate with low traffic reducing the impact on throughput





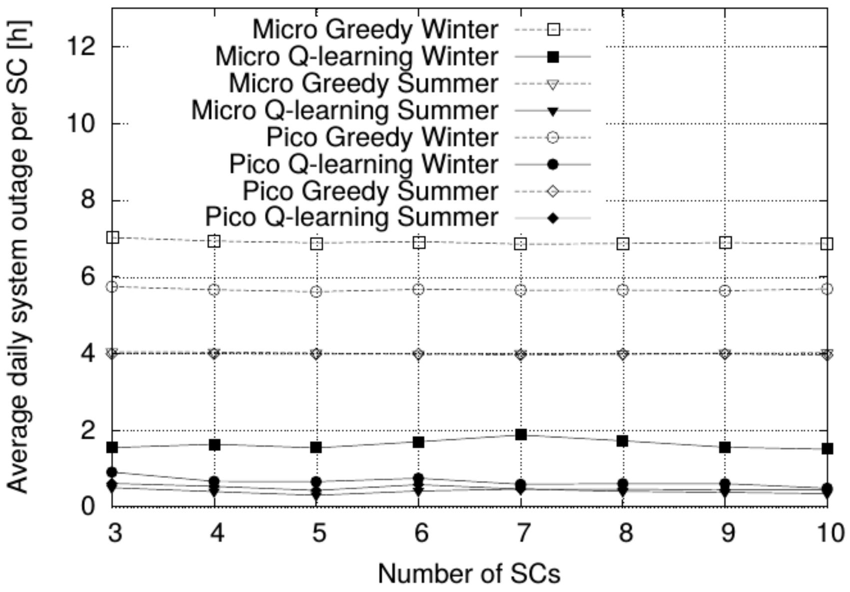
Energy Efficiency

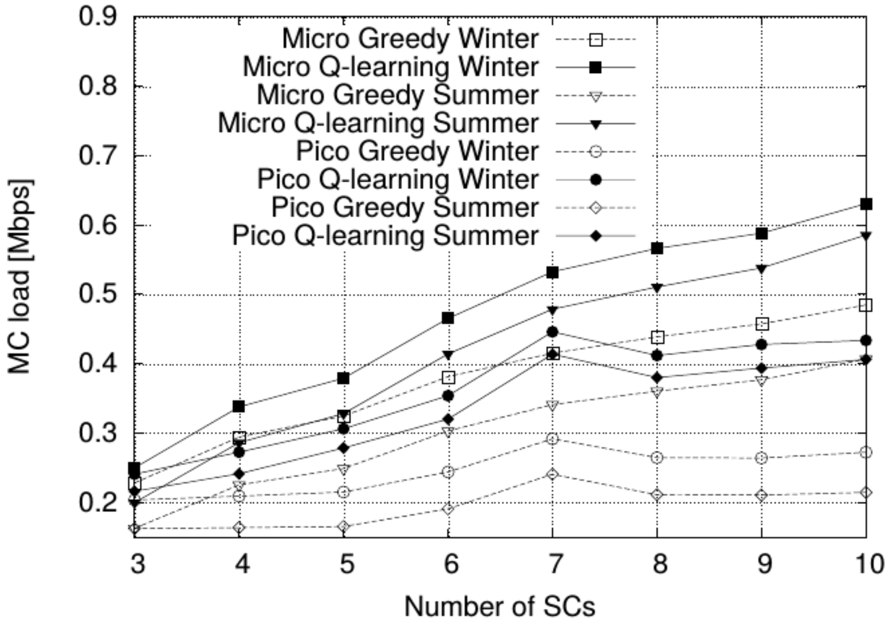
- EE = System Throughput / System Grid Energy
- QL has a greater energy efficiency
- Energy efficiency decreases when number of SCs grows
  - coordination problem among agents
  - spread sleep modes is not efficient with high number of SCs



System Outage and Macro BS Load

- Lower system outage is paid with higher macro BS load



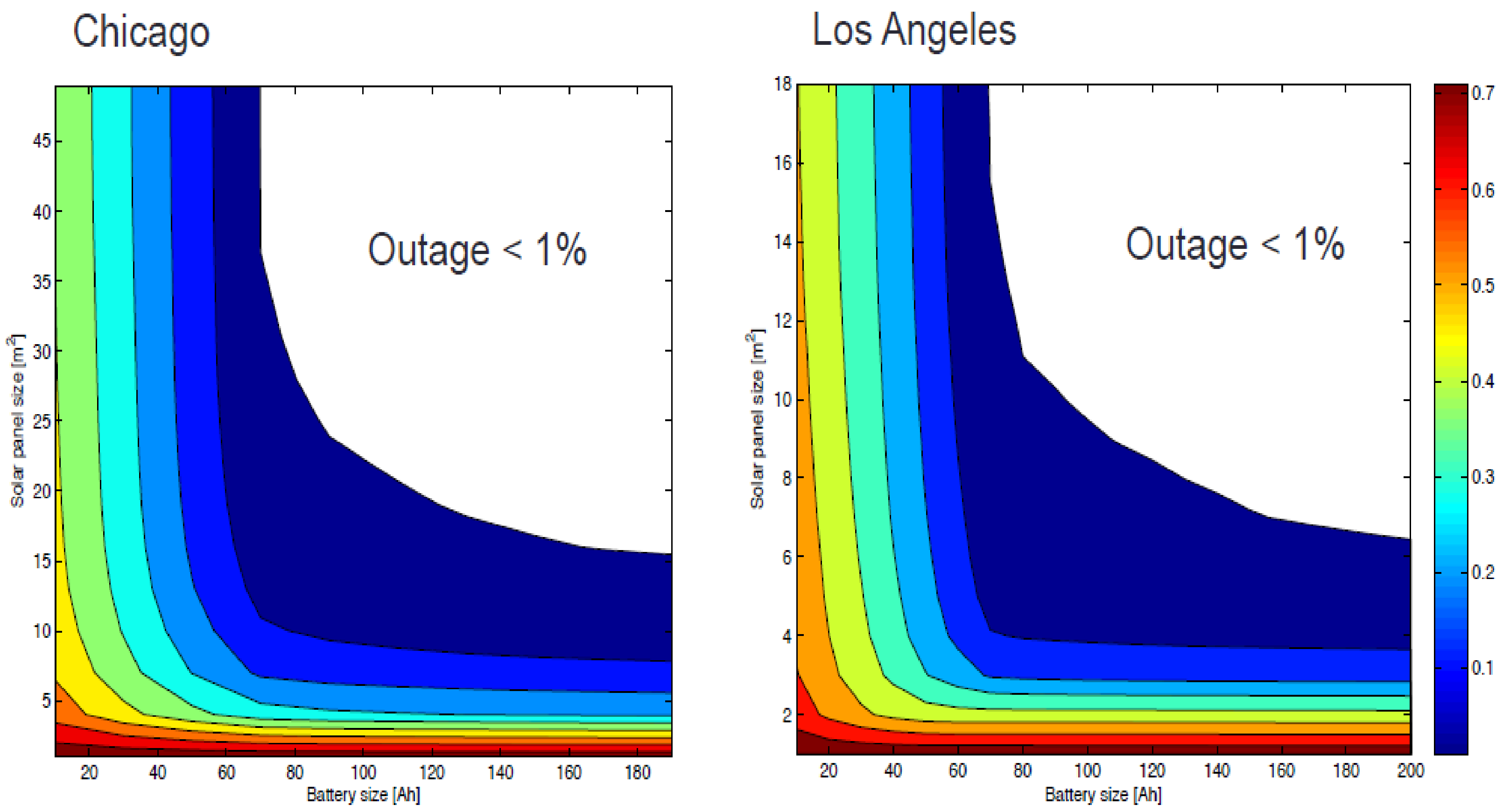


Energy Cooperation

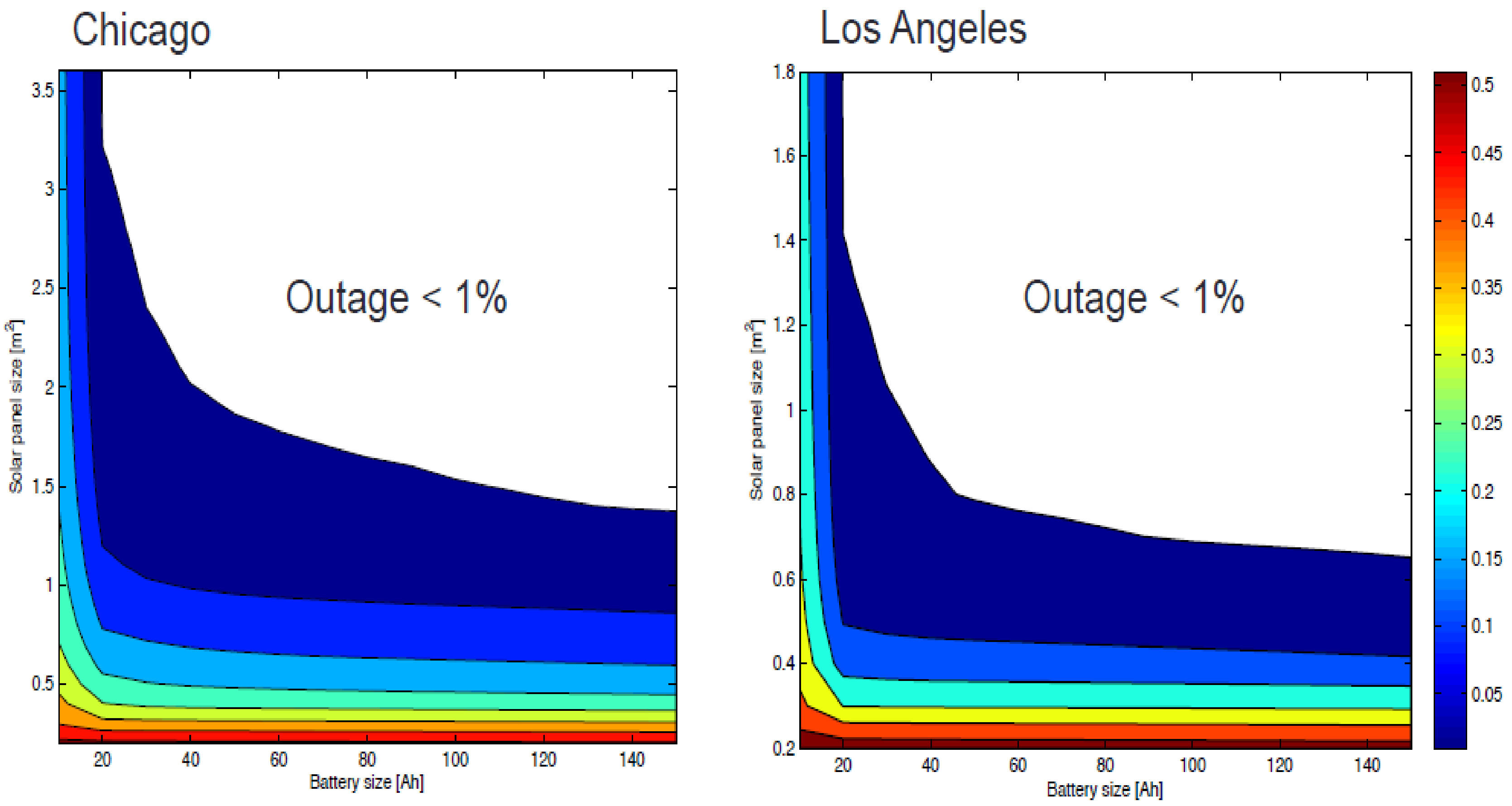
- Future network elements may ***trade some of the energy*** they harvest to make a profit and provide ancillary services to the power grid
  - all HetNet elements: macro and small cells
  - thanks to pricing schemes BSs can sell their excess energy while also making these transactions convenient for the electricity grid:
    - Load balancing
    - Compensation
    - Traffic peaks
    - …

D. Zordan, M. Miozzo, P. Dini, M. Rossi, When Telecommunication Networks Meet Energy Grids: Cellular Networks with Energy Harvesting and Trading Capabilities , IEEE Communication Magazine, Vol. 53, No. 6, pp. 117 - 123, June 2015.

Micro cell


Chicago
Los Angeles
Outage < 1%
Outage < 1%
Solar panel size [m^2]
Battery size [Ah]
45
40
35
30
25
20
15
10
5
20
40
60
80
100
120
140
160
180
18
16
14
12
10
8
6
4
2
200
0.7
0.6
0.5
0.4
0.3
0.2
0.1

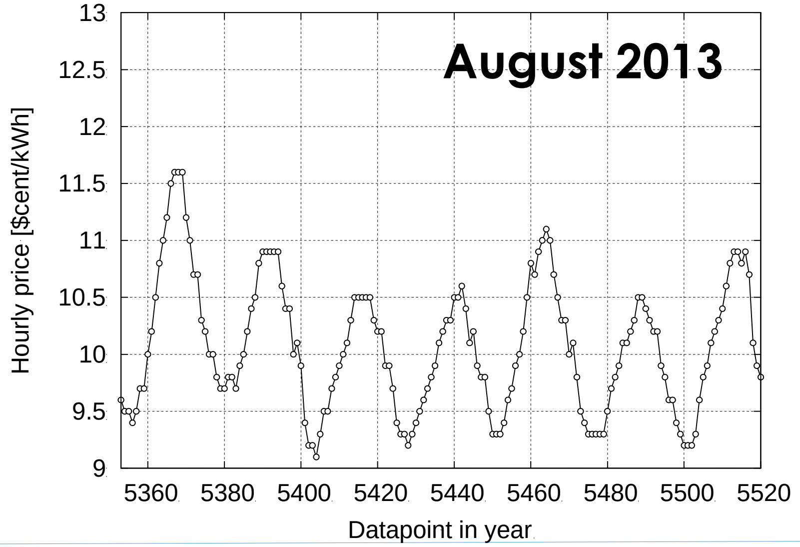
Pico cell

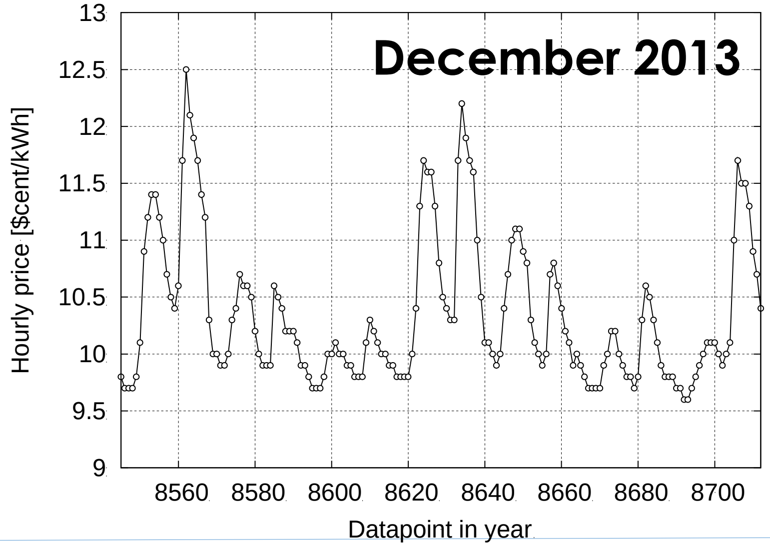


Chicago
Los Angeles
Outage < 1%
Outage < 1%
Solar panel size [m^2]
Battery size [Ah]
3.5
3
2.5
2
1.5
1
0.5
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
20
40
60
80
100
120
140
0.5
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05

Energy Price

- The energy price in future power grids will change hourly
  - In Illinois the midcontinent independent system operator (MISO) set one day ahead the energy price
    - Bell-shape in summer (air conditioning)
    - Bimodal behavior in winter (early morning and evening)

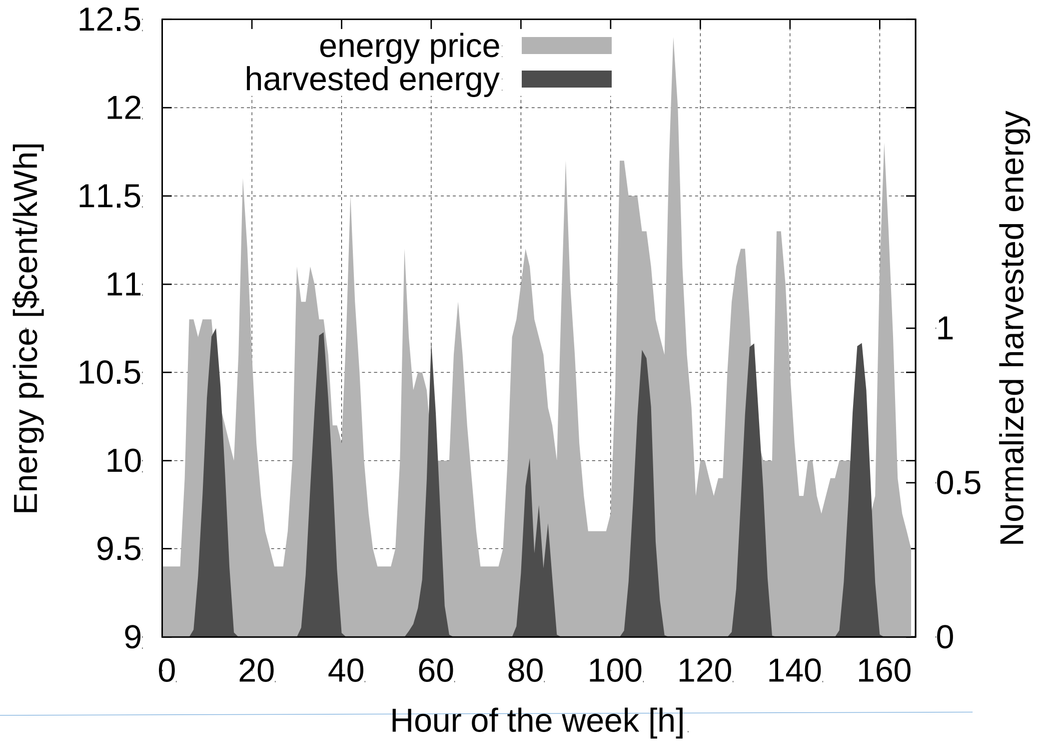




Energy price and normalized harvested energy for the first week of Nov. 2010

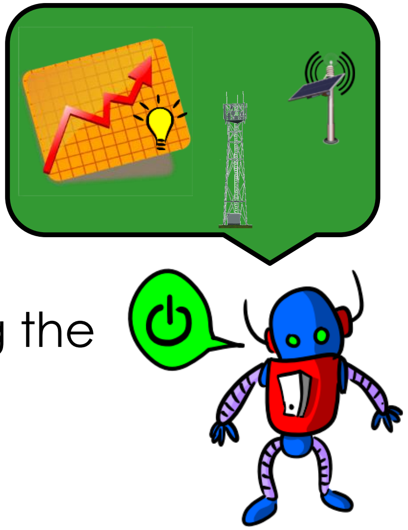
Energy Price

- Optimize network both for energy usage and price
  - Help the system in adapting to prices
  - Redistribute accumulated energy



Optimization problem

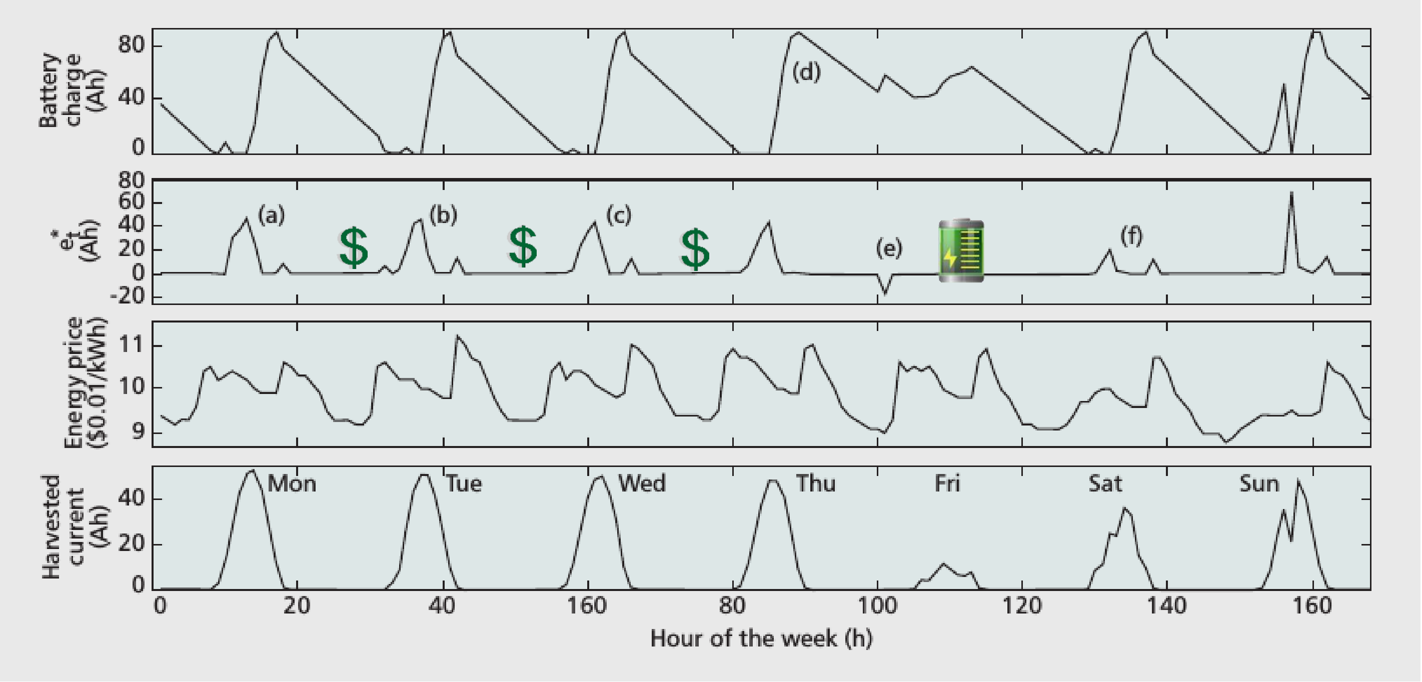
- The system evolves in slotted time t of 1 h.
- At any given time t the BS may sell or buy a certain amount of energy e_t
  - $e_t < 0$: energy has to be purchased with cost $C(e_t)$
  - $e_t > 0$: energy can be sold with a reward $R(e_t) = rC(-e_t)$, where r is a discount factor
- $C(e_t) = 0$ for $e_t \geq 0$ and $R(e_t) = 0$ for $e_t \leq 0$ (no cost is incurred when selling and no reward is accrued when buying).
- At each time t the demand d_t has to be fully served



- Energy Manager decides whether to buy or use stored energy by maximizing the total monetary reward
  - $f(T) = \sum_{t=0}^{T}[R(e_t) - C(e_t)]$, over the time horizon $t \in T = \{0,1,\dots,T)$
  - Find the optimal allocation $\{e_t^*\}_{t\in T}$ through dynamic programming

Policy behavior

- Optimal allocation e_t^* for the third week of November 2010 in Los Angeles
  - *r* = 0.5 for the energy sold
  - Microcell with a panel of 10 m2 and a battery of 90 Ah (at 24 V)



- a), c) and d) is optimal to sell energy, e_t^* has positive peaks and battery is already charged
- e) energy purchasing, low income

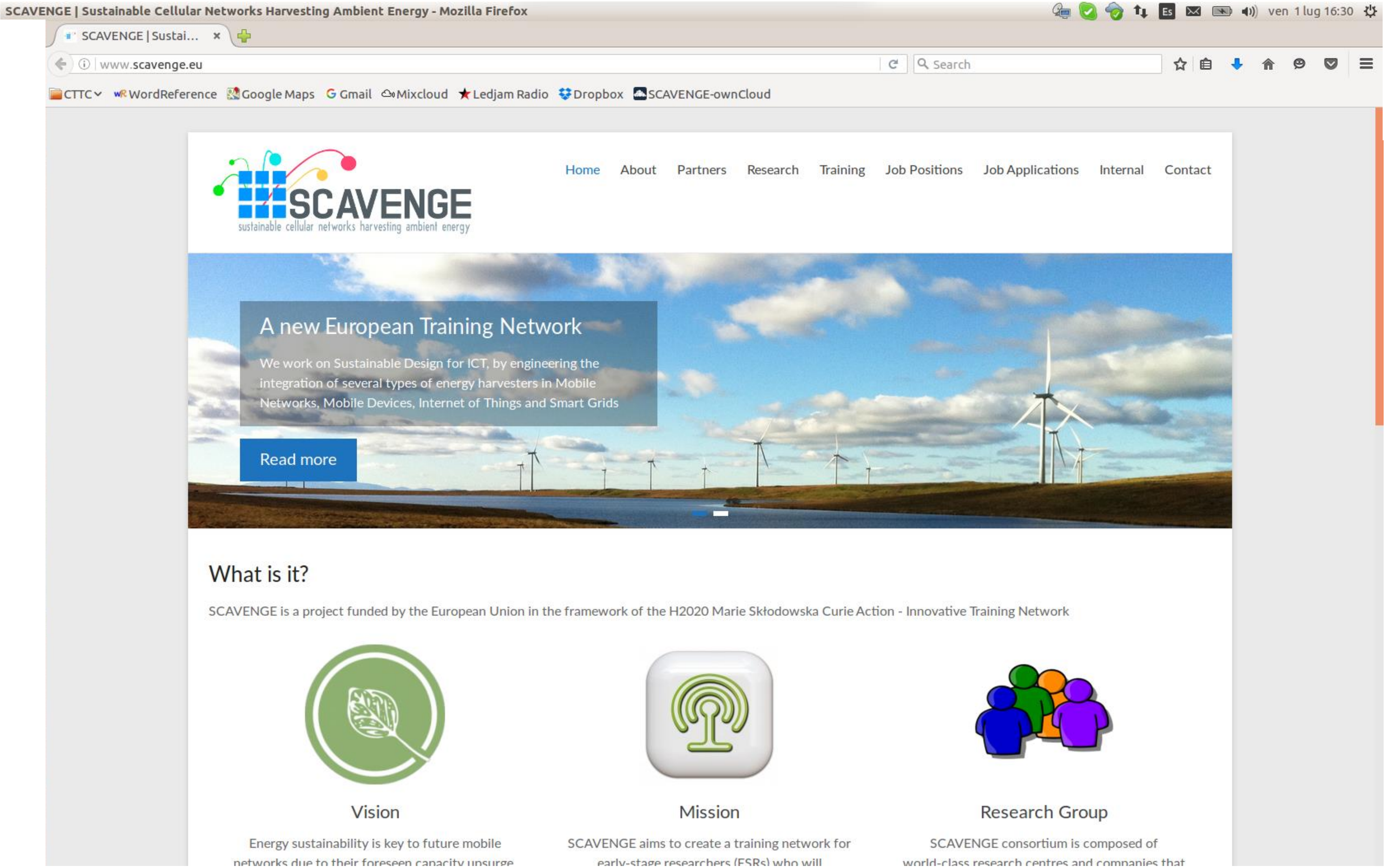

Energy Trading Results - CAPEX

- Dimension the solar add-on in order to maximize the net profit in 10 years using e_t^*: $f(T) + E_{BS}^{grid} - CAPEX$
  - $f(T)$ is the revenue defined before
  - E_{BS}^{grid} cost of energy when BS is powered only by grid
  - $CAPEX$: solar panels $0.5/kWh and battery $300/kWh

- Two design philosophies
  - D1 min space constraints
  - D2 max profit
- Positive income in almost all cases

"$*X* (*Y*, *Z*)," where *X* is the net income in U.S. dollars, *Y* is the solar panel size square meters), and *Z* is the battery size (Ah)

	Chicago			Los Angeles		
BS type	D1 (net income)	D2 (net income)	D2 (annual revenue)	D1 (net income)	D2 (net income)	D2 (annual revenue)
Pico	$19 (1, 20)	$58 (2, 20)	$71	$51 (1, 20)	$117 (2,20)	$130
Micro	$232 (10, 80)	$607 (20, 80)	$709	$544 (10, 80)	$1193 (20, 80)	$1295
Macro	-$1566 (60, 500)	-$695 (80, 500)	$1395	$466 (60, 500)	$1813 (80, 500)	$2586


SCAVENGE | Sustainable Cellular Networks Harvesting Ambient Energy - Mozilla Firefox
ven 1 lug 16:30
SCAVENGE | Sustai...
www.scavenge.eu
Search
CTTC
WordReference
Google Maps
Gmail
Mixcloud
Ledjam Radio
Dropbox
SCAVENGE-ownCloud
SCAVENGE
sustainable cellular networks harvesting ambient energy
Home
About
Partners
Research
Training
Job Positions
Job Applications
Internal
Contact
A new European Training Network
We work on Sustainable Design for ICT, by engineering the integration of several types of energy harvesters in Mobile Networks, Mobile Devices, Internet of Things and Smart Grids
Read more
What is it?
SCAVENGE is a project funded by the European Union in the framework of the H2020 Marie Skłodowska Curie Action - Innovative Training Network
Vision
Energy sustainability is key to future mobile
Mission
SCAVENGE aims to create a training network for
Research Group
SCAVENGE consortium is composed of

Thanks for your kind attention

Centre Tecnològic de Telecomunicacions de Catalunya

Paolo Dini

Senior Researcher
Communication Networks division
paolo.dini@cttc.es
http://www.cttc.es/people/pdini/

"The world has enough for everyone's need, but not enough for everyone's greed." (Mahatma Gandhi)