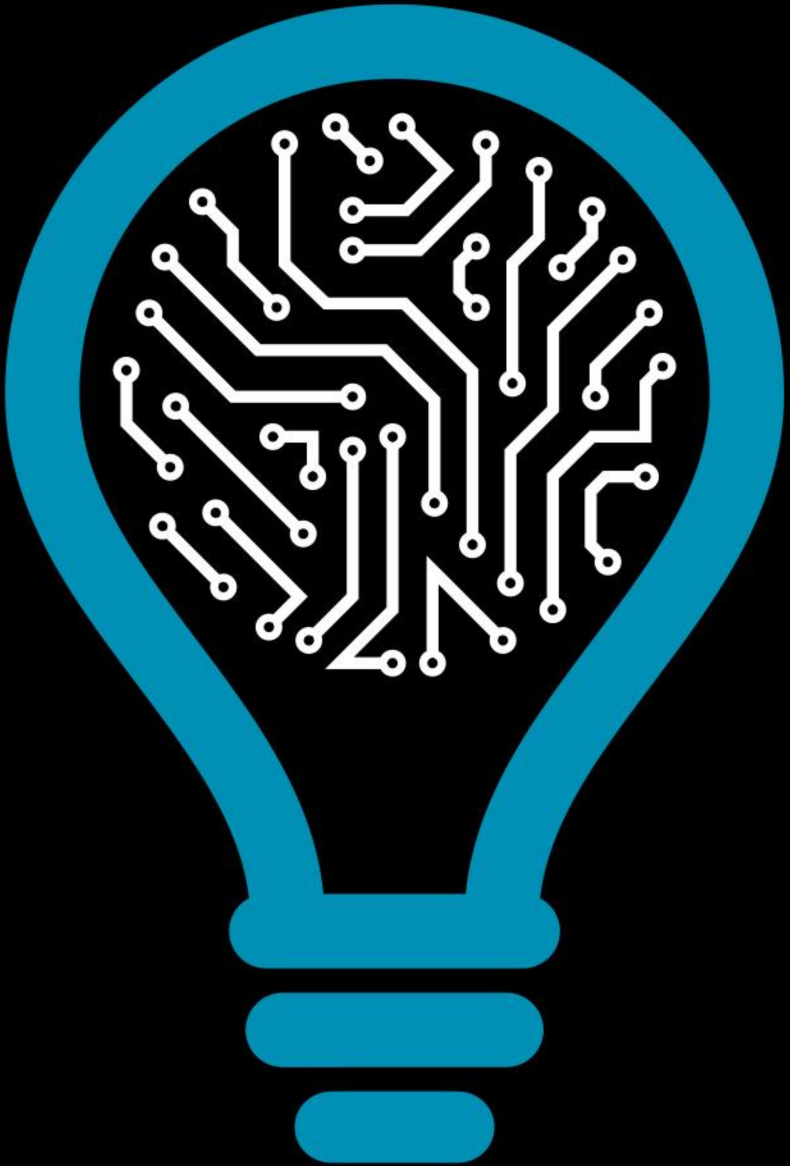
The challenges of large scale RES integration

Past and future in Portugal and elsewhere

Vladimiro Miranda may 2018

INESCTEC
INSTITUTE FOR SYSTEMS AND COMPUTER ENGINEERING, TECHNOLOGY AND SCIENCE



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The good news is...

THE INDEPENDENT

News > World > Europe

Lydia Smith | Thursday 5 April 2018 12:52 BST

Renewable energy generated 104% of Portugal's electricity consumption in March (...)

Hydroelectric dams accounted for 55 per cent of monthly energy consumption and wind power made up 42 per cent.

No blackouts, no collapse of the power system...

HOW IS THIS POSSIBLE?

Conditions for a large scale seamless integration of new renewables in a traditional system

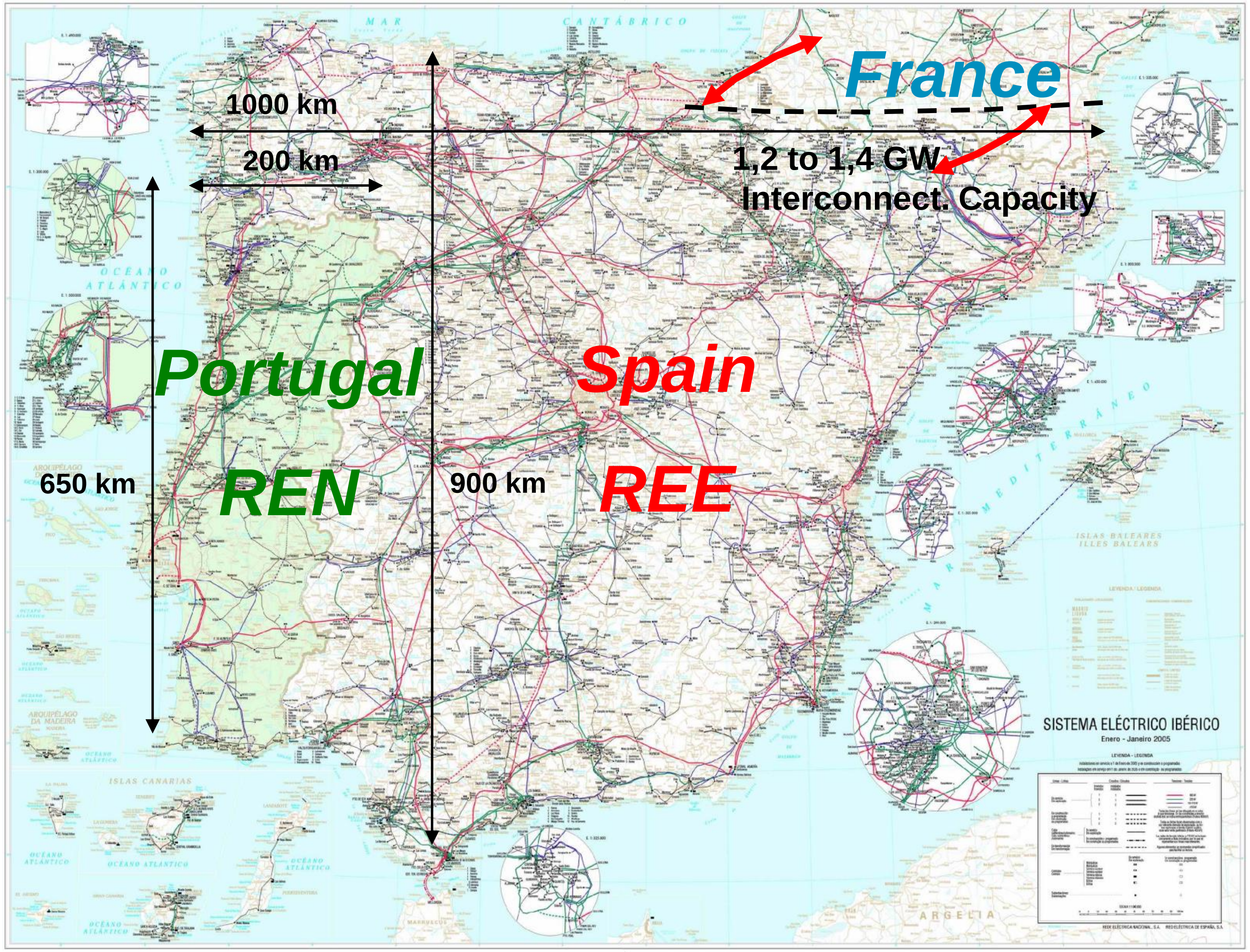
Some topics to consider:

- Dispersion, diversity of sources – to benefit from positive statistical effects
- Redesign of the transmission system
- Smart grids, micro-grids at distribution level
- Interconnections with neighbors
- Storage (preference: in the form of pumped storage)
- New planning tools
- New forecasting tools
- New operation tools
- Evolve from classical deterministic thinking to probabilistic/risk thinking
- Redesign markets
- Adapt regulation

Iberia: two countries, two TSO – December 2016

Population
10.3 million
Installed Capacity
19.5 GW
Peak power
8.6 GW
Installed wind
5.4 GW

Population
46.6 million
Installed Capacity
105.3 GW
Peak power
40.5 GW
Installed wind
23.0 GW

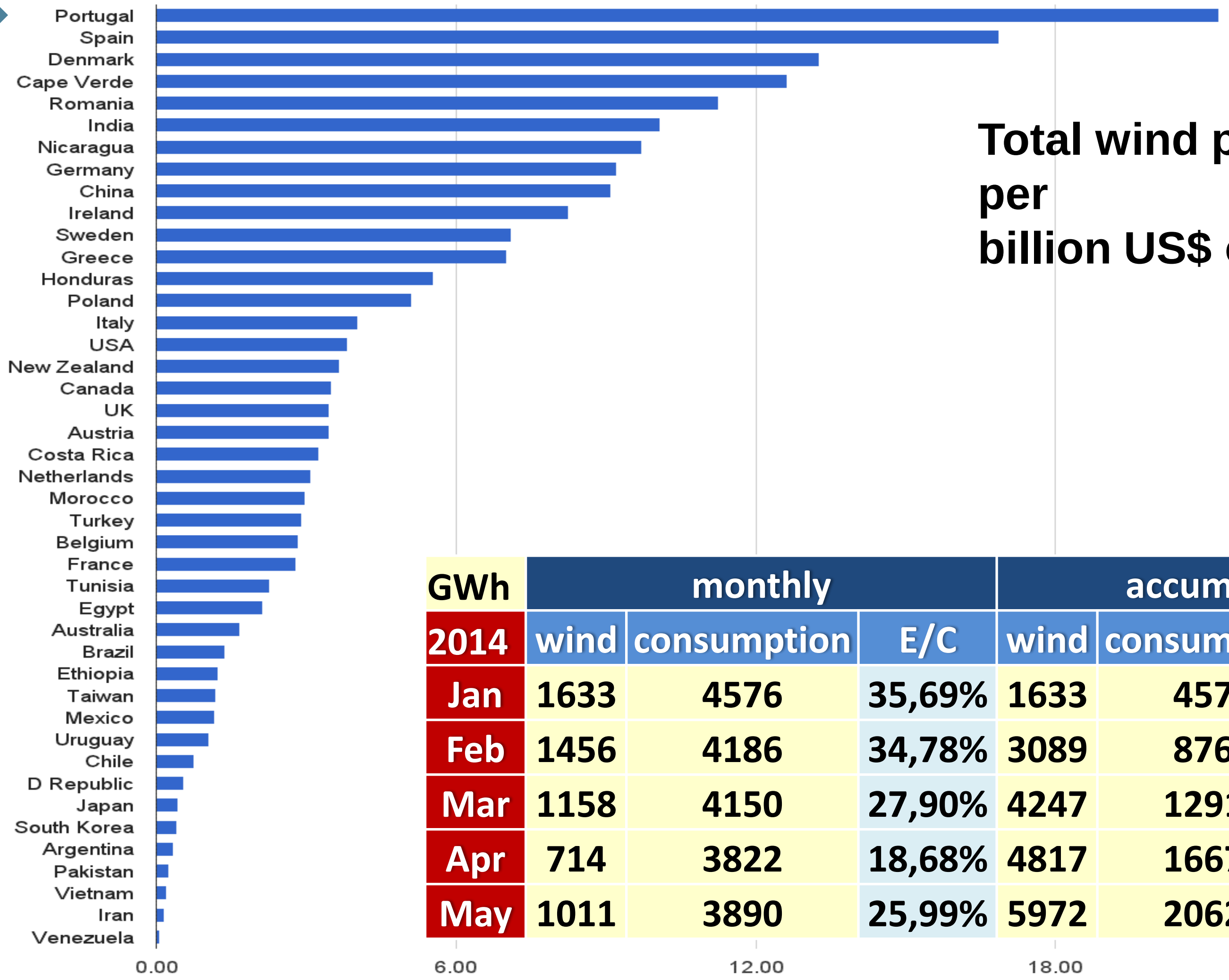


Acknowledgment: REN – Redes Energéticas Nacionais (kind permission: Engº Vítor Baptista)

Portugal is the country in the world where wind power is more relevant in the creation of wealth

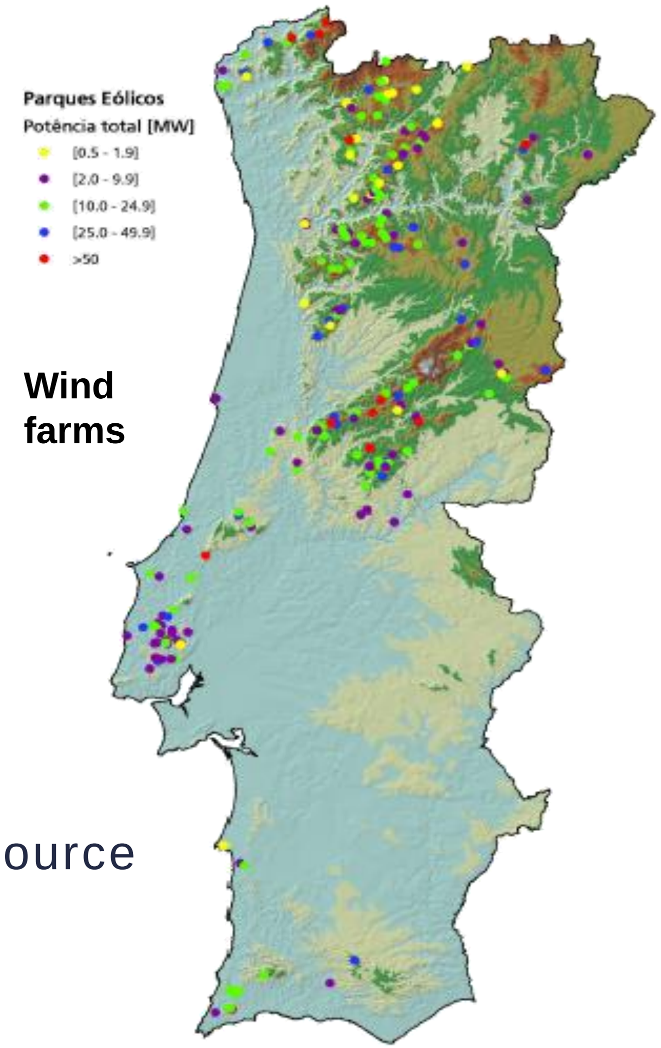
1 PORTUGAL

Total wind power MW per billion US$ of GDP

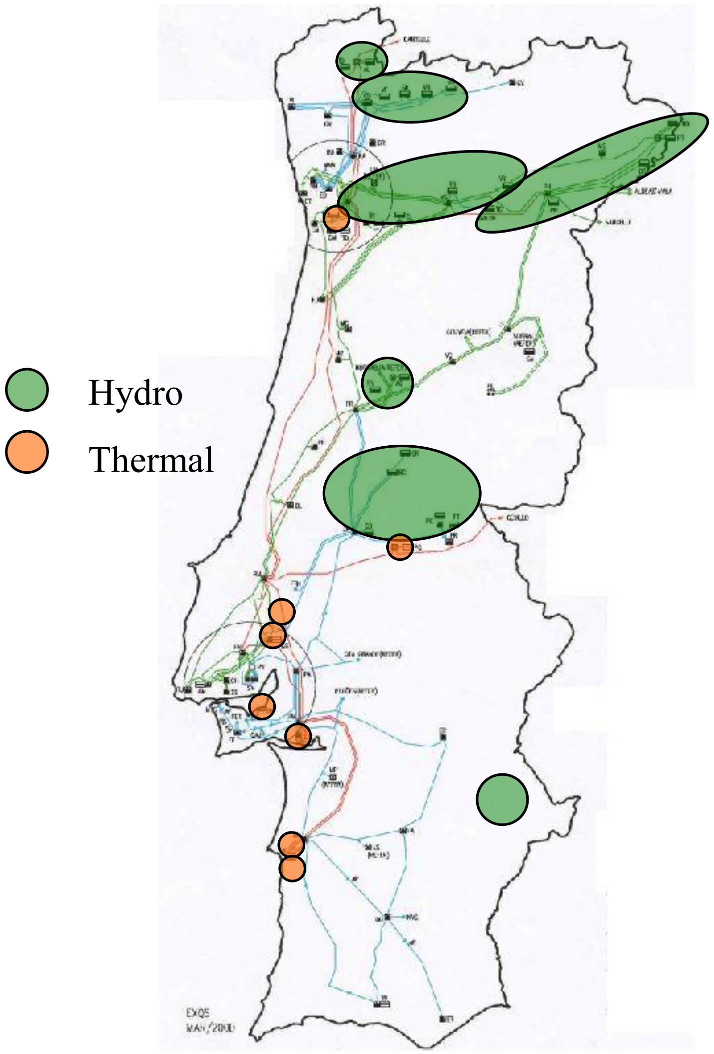


GWh	monthly			accumulated		
2014	wind	consumption	E/C	wind	consumption	E/C
Jan	1633	4576	35,69%	1633	4576	35,69%
Feb	1456	4186	34,78%	3089	8762	35,25%
Mar	1158	4150	27,90%	4247	12912	32,89%
Apr	714	3822	18,68%	4817	16678	29,65%
May	1011	3890	25,99%	5972	20624	28,96%

Wind, hydro and thermal generation in Portugal: a geographical asymmetry



Wind farms



Asymmetry of resource distribution!

Acknowledgment: REN – Redes Energéticas Nacionais (kind permission: Engº Vítor Baptista)

You have a seamless integration of wind power if you have a transmission grid designed to accommodate it

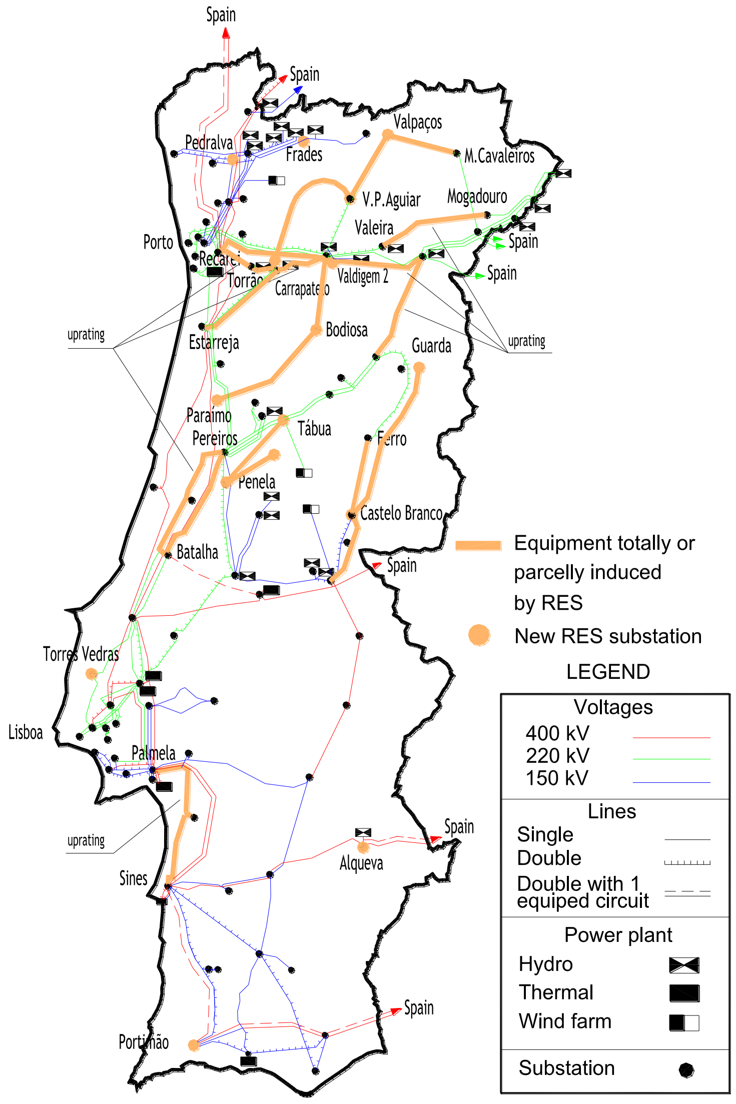
Portugal redesigned the transmission system, including new lines and substations and anticipating the scheduling of others previously planned.

The map shows key items in orange, including the following :

- Uprating of existing lines and substations
- New lines and substations
- Development of new substation bays
- Boosting reactive energy compensation capabilities

Reasons to reinforce the grid

- High penetration of RES causes higher movement of energy in the grid
- It is necessary to collect wind at far away load centre areas
- More transmission capacity was needed from wind generation areas to load areas (costal regions) and to Spain

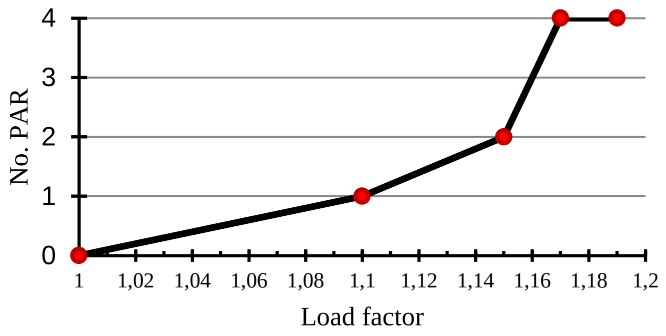


Acknowledgment: REN – Redes Energéticas Nacionais (kind permission: Engº Vítor Baptista)

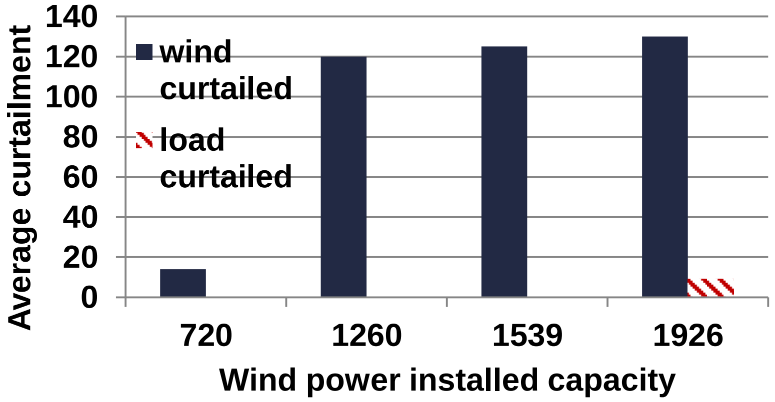
More energy movement demands a flexible transmission system Instead of reinforcing lines… install FACTS: PAR/PST

The problem is solved with multiple scenario Stochastic Optimization, taking in account wind and load uncertainty.

In a study case, for 8 possible locations of PAR/PST in a large system, the optimal number of PAR/PST was depending on the load level:



With PAR/PST, the wind spilling is minimized



With a high penetration of renewables, is Iberia safe? YES.

In 2005, the system operators of Spain and Portugal (REE and REN) asked INESC TEC to develop a model to evaluate the security of supply until 2025, and assess levels of operational reserve, under a reliability perspective.

RESERVAS was born: a full-fledged efficient Sequential Monte Carlo based model, representing:

- Conventional thermal generation (fossil fuels and nuclear)
- Large reservoir, large run-of-the-river hydro generation
- Mini-hydros
- Independent generation, CHP
- Wind power
- Load and resource availability scenarios
- Operation strategies and maintenance

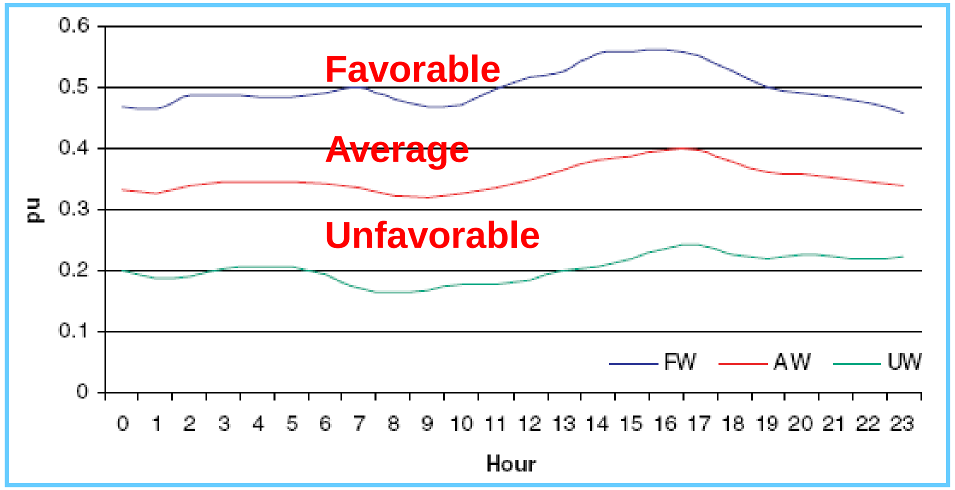
RESERVAS validated the strategies to be implemented.

RESERVAS became a reference model in Europe.

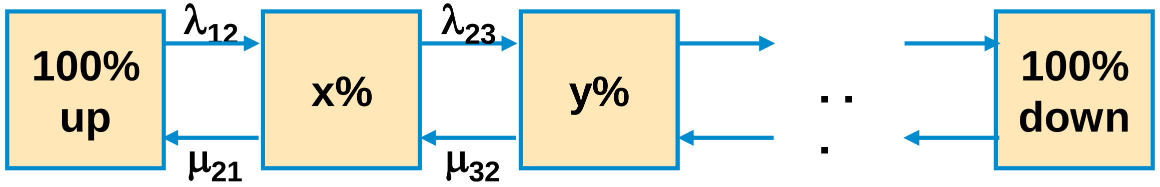
Wind power: a geographical and seasonal representation in RESERVAS

The country was divided in wind regions according to the behavior of historical wind series.

Wind in each region: series clustered in wind regimes



Wind generation: a multiple stage Markov model



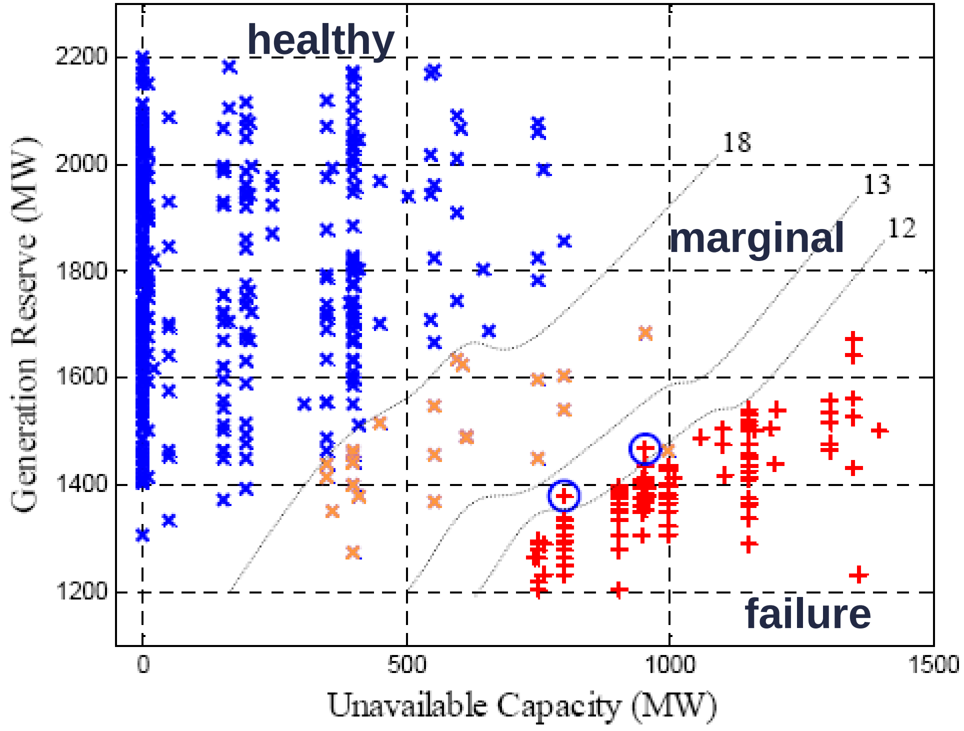
Computational Intelligence inside Monte Carlo

Significant features are selected to identify each state: like the generation reserve, the unavailable generating capacity and the unavailable transmission capacity.

They allow a partition of the states recognized by a NN, performing pattern recognition.

States recognized as healthy:

- ✓ no need for simulation
- ✓ computing time spared!



Example for a 26 bus test system with two areas of 230 and 138 kV

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New advances in Monte Carlo efficiency: Cross Entropy

A striking example: Brazilian South-Southeastern System

67 generation plants, 290 units, 45.6 GW of installed capacity

Hourly load model, 8736 levels, peak 41.2 GW, LOLP = 1.909×10^{-5}

Estimation of LOLP via Monte Carlo: acceleration obtained with CE-based importance sampling:

Computing times *	β = 1%	β = 5%
Crude MC	26 hours	
CE - MC	31.6 seconds	3.3 seconds

**computations performed in a MATLAB platform using an Intel Core 2 Duo 2.66 GHz processor.*

The new model MORA

In 2017/18, INESC TEC developed the MORA model: again a Sequential Monte Carlo simulation, now including the transmission system and its operational characteristics, as well as wind and solar and other NRE sources, pumped storage and other features.

Iberia (Portugal + Spain) has the most advanced model in the world in terms of comprehensive probabilistic simulation of power systems with a large penetration of all sorts of renewable sources.

Even in extreme scenarios of unbalanced supply, the Portuguese and Spanish systems offer an extremely high expectancy of a secure operation, rewarding citizens with such a degree of security that people take electricity supply for granted – and the world is surprised, because the dark pessimistic predictions of collapse for a system with “too many intermittent renewables” are totally contradicted by reality – thanks to Iberian planning, science and technology.

You have a seamless integration of Wind Power if you have hydro power + pumped storage

As early as 2007, the Ministry of Environment launched a National Plan for Hydro (NPH)

- *8 new hydro power stations (HPS), almost all of them reversible*
- *This would multiply by at least 2* the foreseen installed MW capacity*

The NPH, together with other new hydro projects, would secure almost new 5,0 GW of hydro generation + pumping capacity

The plan has been readjusted, but the bottom-line is:

wind power + hydro power + storage is a magic recipe

Courtesy: REN – Redes Energéticas Nacionais (Engº Vítor Baptista)

Wind and pumped hydro storage combine very well

Motivation

It may be shown that the synergic operation of wind farms with a pumping strategy adds value to energy, beside improving the value of reserves in storage

This allows a double justification:

- With pumping available, the investment in wind power becomes more profitable
- With wind power available, the investment in pumping becomes more profitable

THE INNOVATION IS IN THE EXPLOITATION OF THE SYNERGY!

THE SECRET:

Wind-hydro synergy

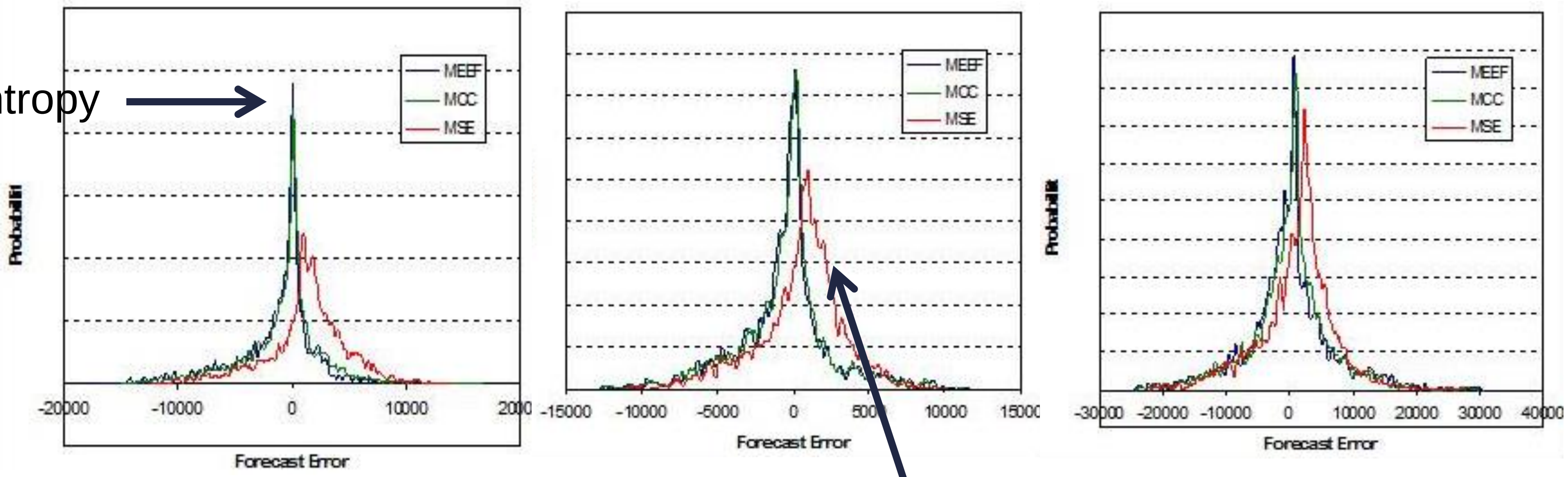
Renewables demand prediction – and predictors trained with information entropy concepts lead to better results

Comparing error pdf for 3 real wind farms in Portugal:

.

A B C

Min Entropy



A substantially worse error result is obtained for MSE

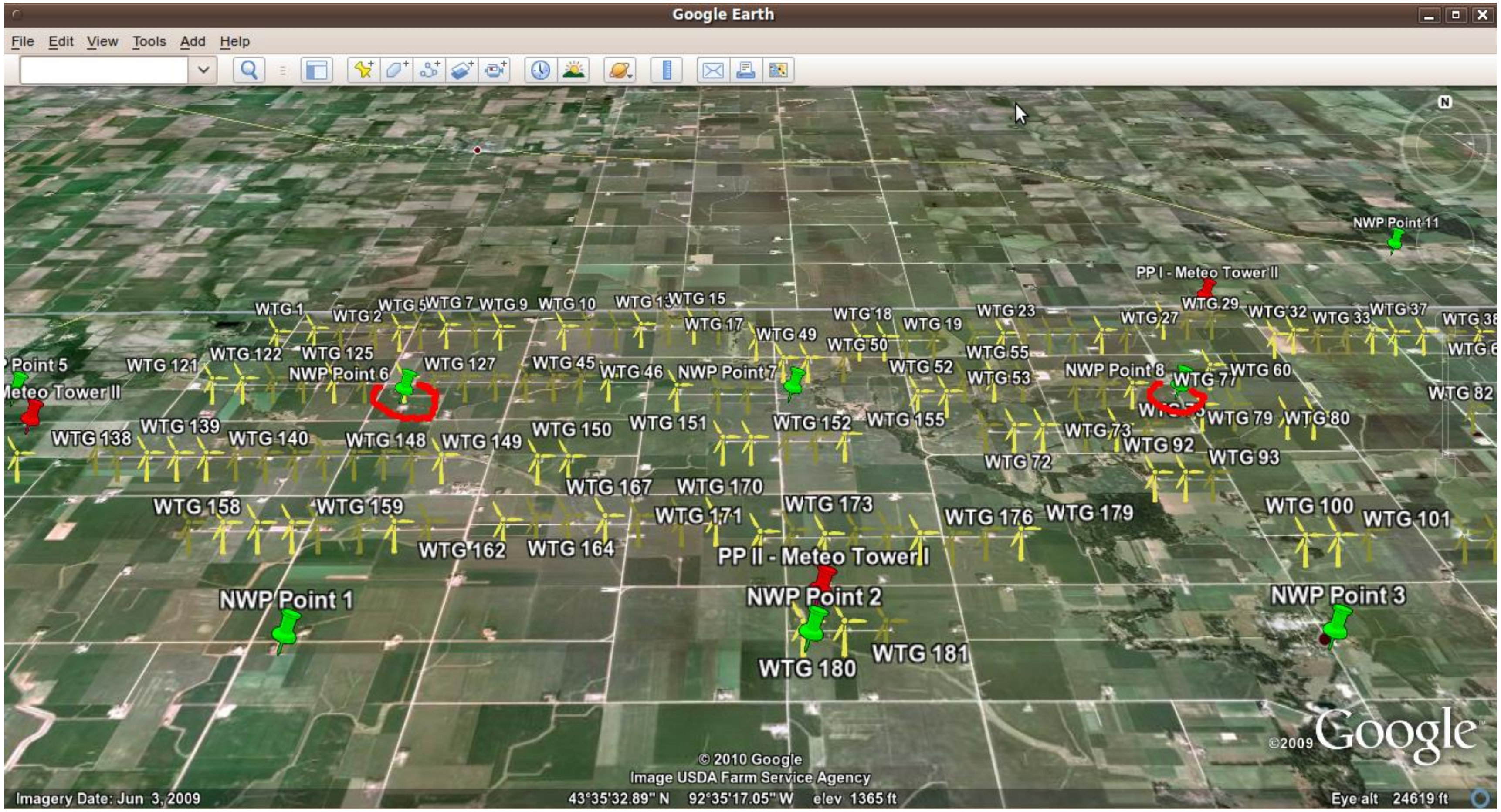
– it displays lower frequency of errors close to zero.

Entropy models: improvement in prediction quality in 72 h ahead predictions

Application in the USA

Geo-referenced data for each wind generator

NWP: 11 points defined by the ANL, 2 taken for the preliminary studies



ARGUS PRIMA – Prediction Intelligent Machine *

INESC TEC software package made available:

- PostrgreSQL database
- NN library in C++, implementing several ITL criteria
- Kernel density forecast library in R
- Supporting codes in Python and R

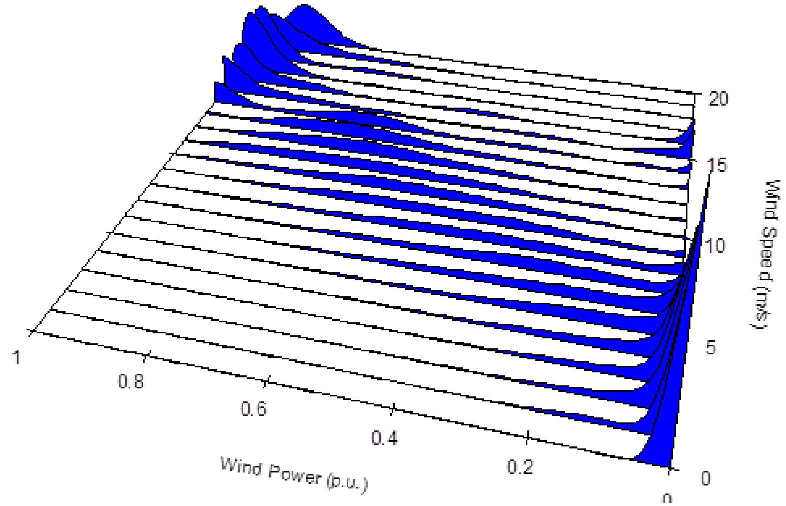


Illustration of uncertainty estimation with KDF (kernel density forecast): stacked conditional probability density function plot for wind power as a function of forecasted wind speed

* made available from ANL (USA) or through INESC TEC (Portugal)

http://www.anl.gov/technology/project/argus-prima-wind-power-prediction

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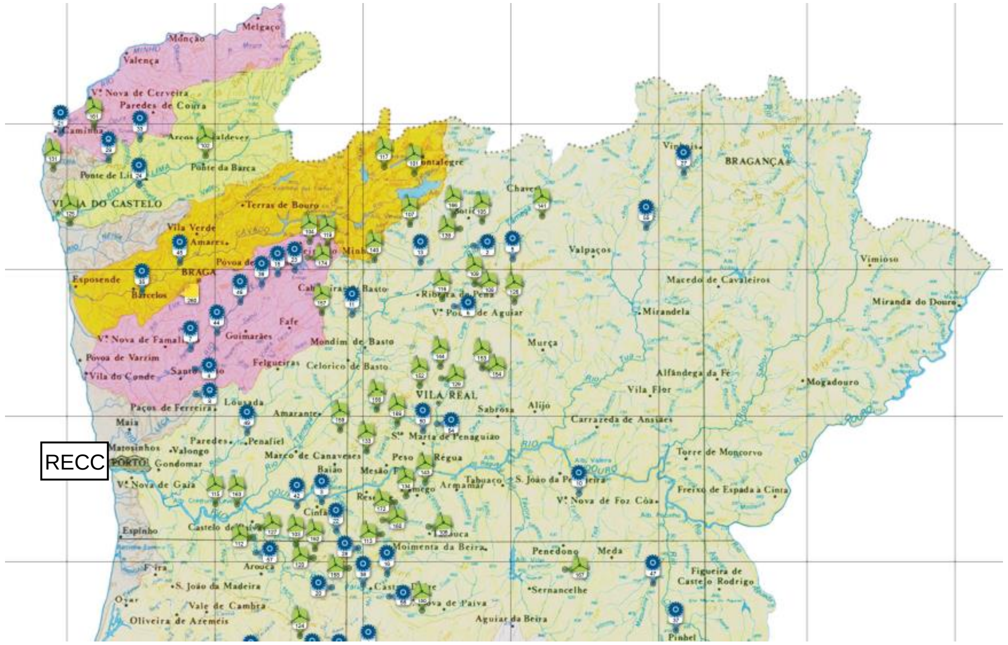
INESC TEC - the implementation experience at wind farm level

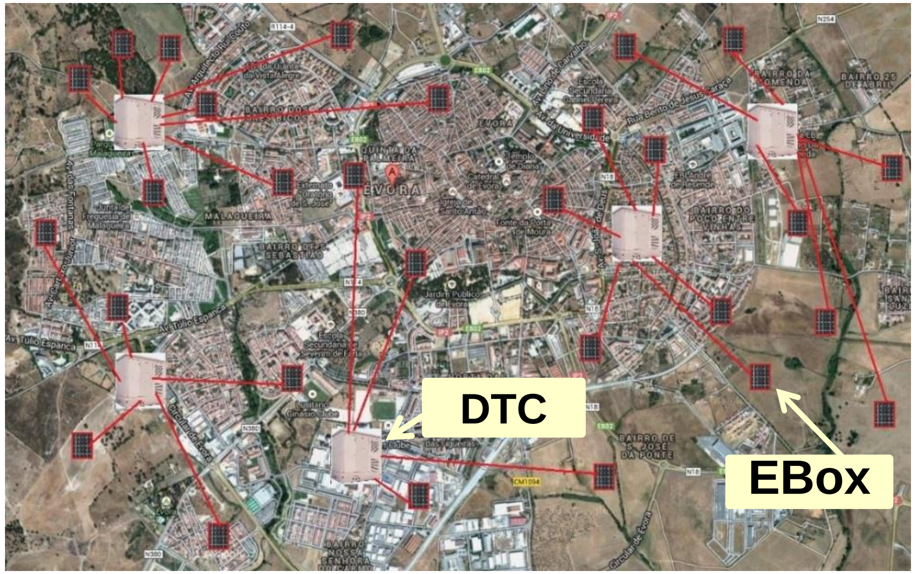
INESC TEC implemented the Wind Power Forecasting models and system for the Renewable Energy Control Center, to:

- Supply wind generation forecasts for system operator
- Plan the use of hydro energy storage
- Plan maintenance of the wind farm for the next days
- Make bids in electricity markets
- Wind farm management



Prewind

EVORA, Portugal: the pioneer pilot Smart City



Aparecida, Brazil: InovCity socially adapted

Evora pioneered the Energy Box concept when others were massively deploying crippled Smart Meters with limited functions

Smart (?) Meter

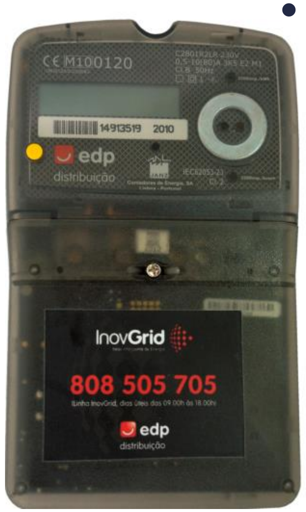
- Records consumption
- Two-way communication
- Near real time
- Power outage notification
- Power quality monitoring

Energy Box

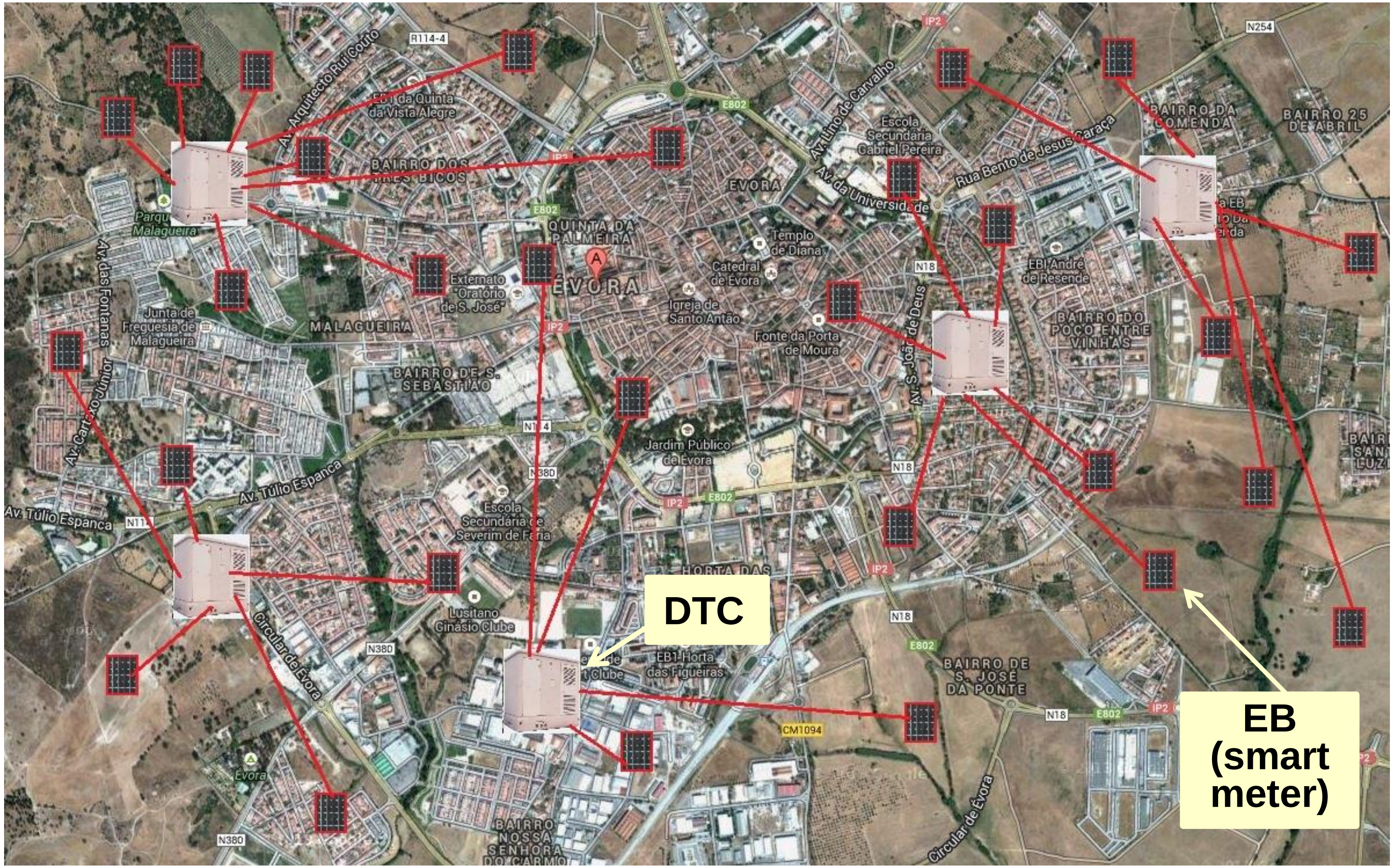
- All functions of a Smart meter

plus

- Management of local generation
- Management of local storage
- Electric vehicle charging
- Smart appliances control

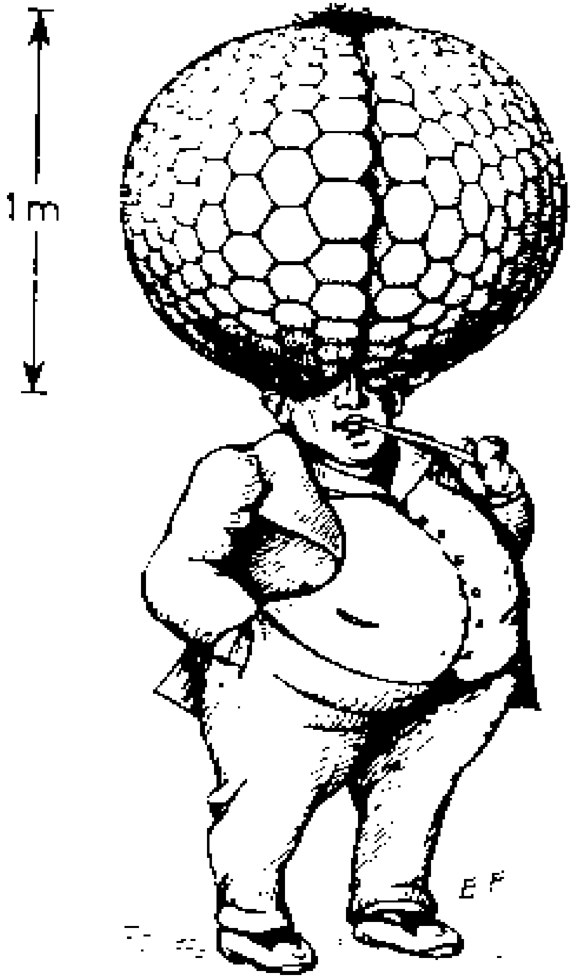


Territorial distribution of PV with Evora as example



Distributed PV: a retina

Mirroring the sky in the pixels of the eye



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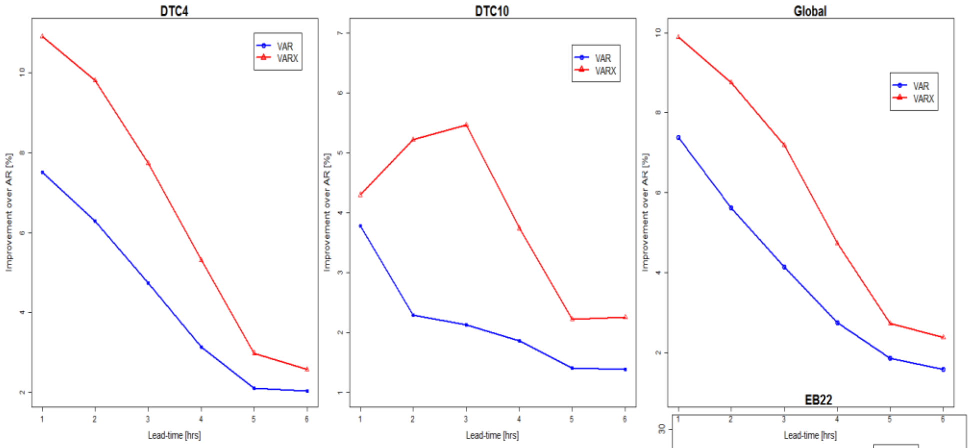
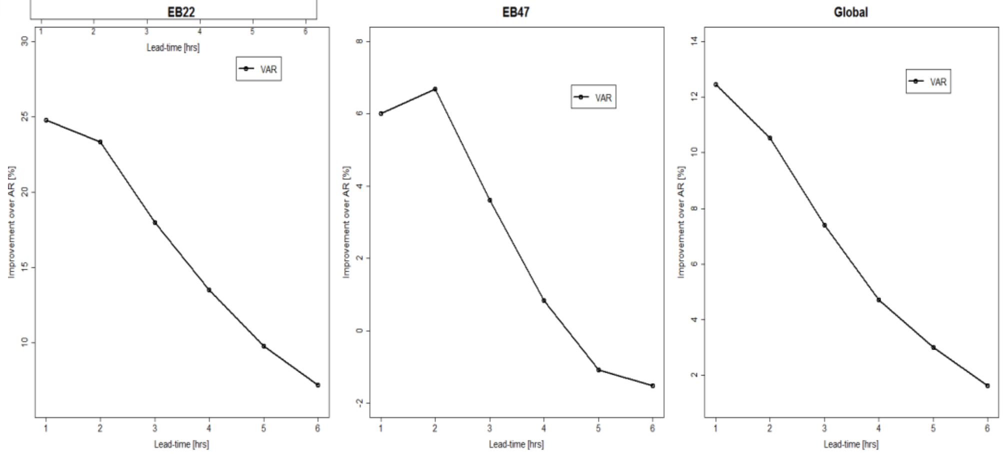
Better solar power forecasting with vector models – extracting value from the smart grid

Statistical VAR and VARX models - reducing the prediction error compared to an AR time series model, thanks to the space-temporal data collected by the Smart Grid infrastructure, through the Energy Boxes (EB) and condensed at the DTC (Distribution Transformer Control).



At DTC level:

over 10% reduction in prediction error, when compared to a simple AR model, in the 1st hour



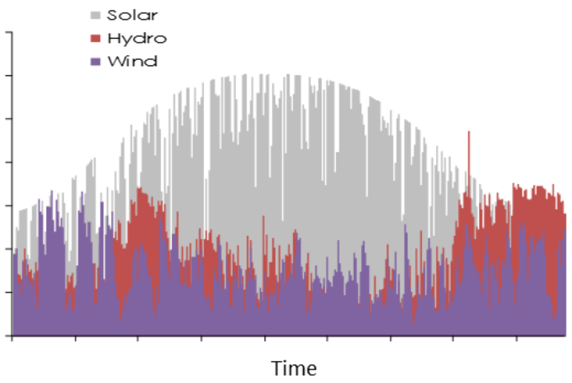
At individual consumer level:

from 6 to 24% improvement in error reduction , in the 1st hour

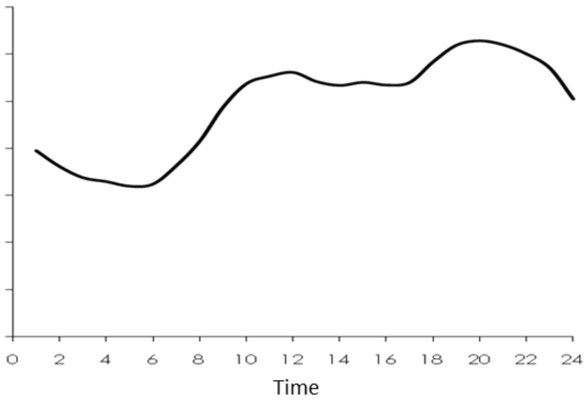
What are the challenges for RES Integration?

Negative Correlation

RES: Generation pattern %

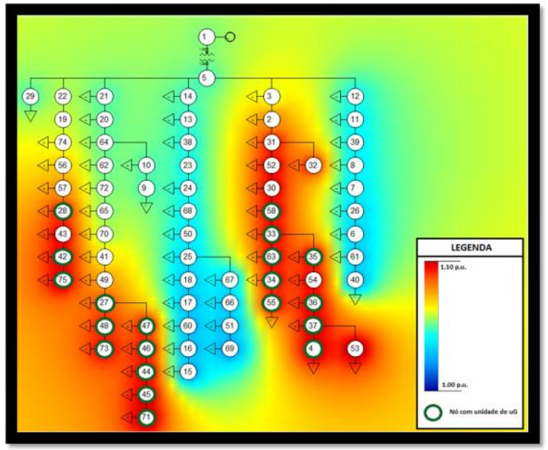


Consumption Pattern GW

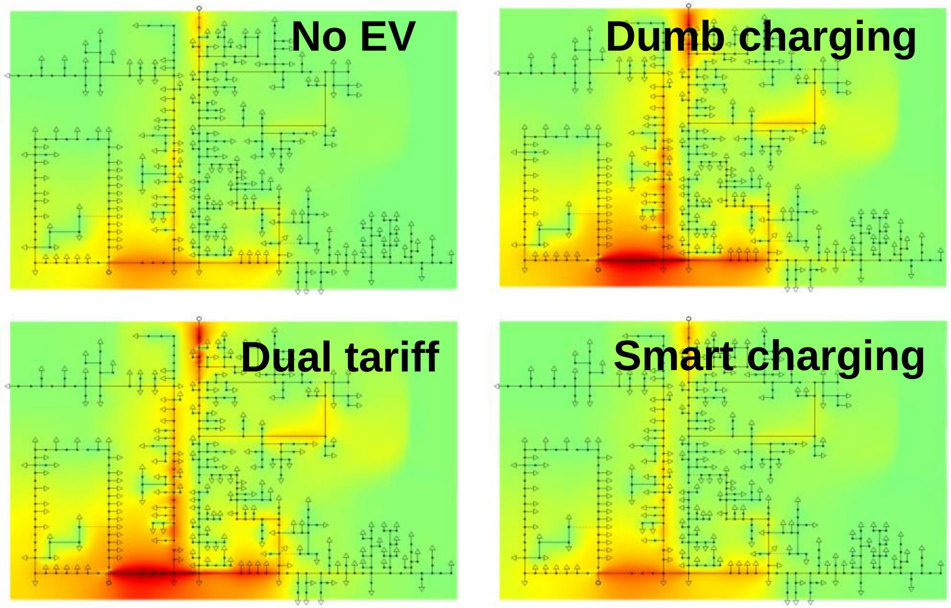


Local Technical Impacts

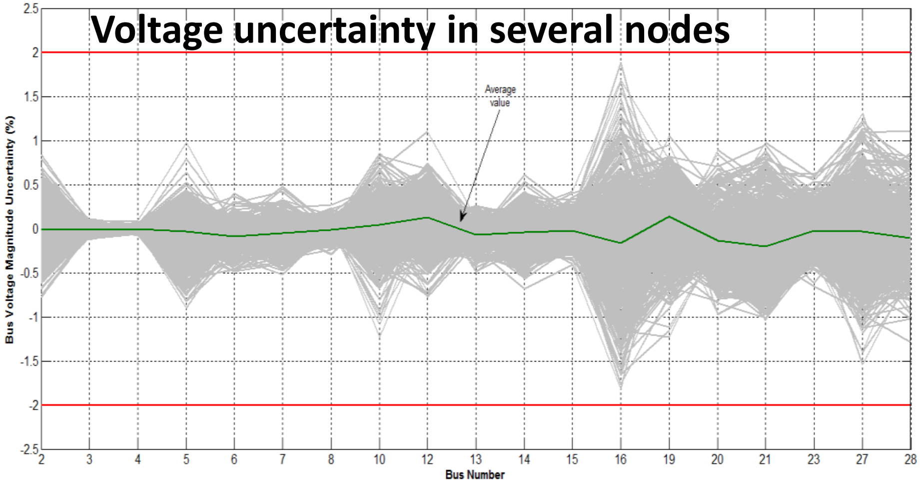
RES Integration

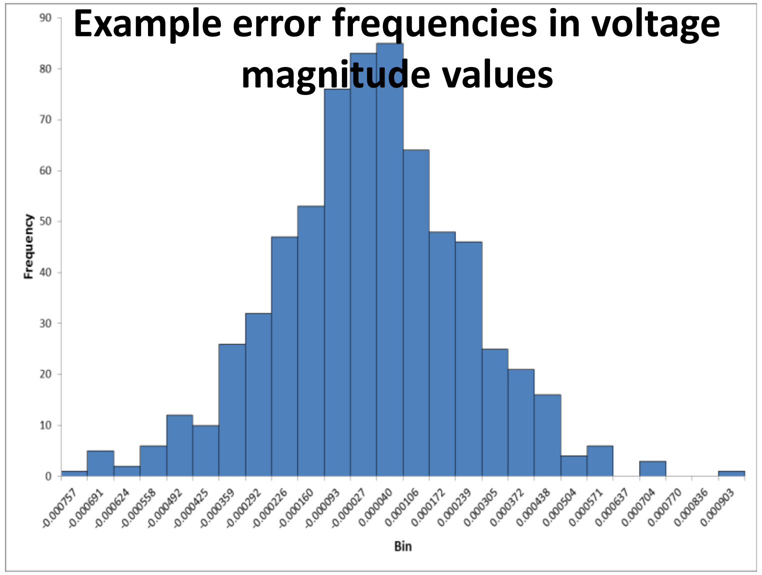


What about EV?

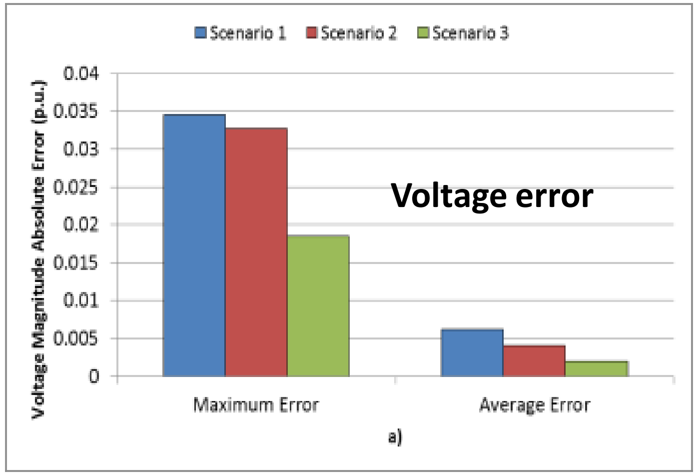


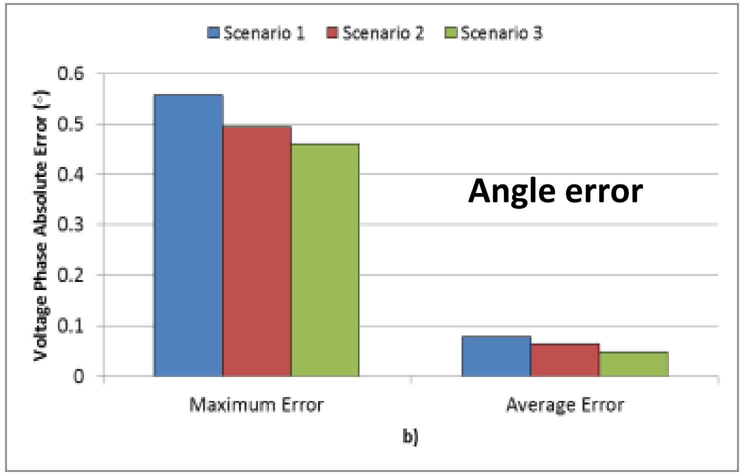
An LV state estimator, baased on autoencoders, was developed for smart grid environments





Maximum and average estimation error





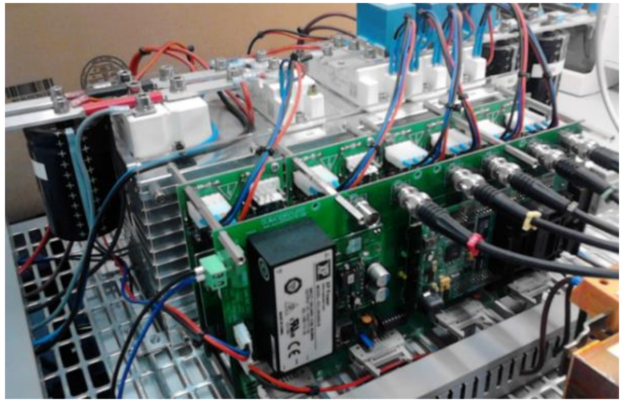
INESC TEC WISE SISE technology

Wind Integration in Smart Environments — W I S E

Solar Integration in Smart Environments — S I S E

For weak connection points:

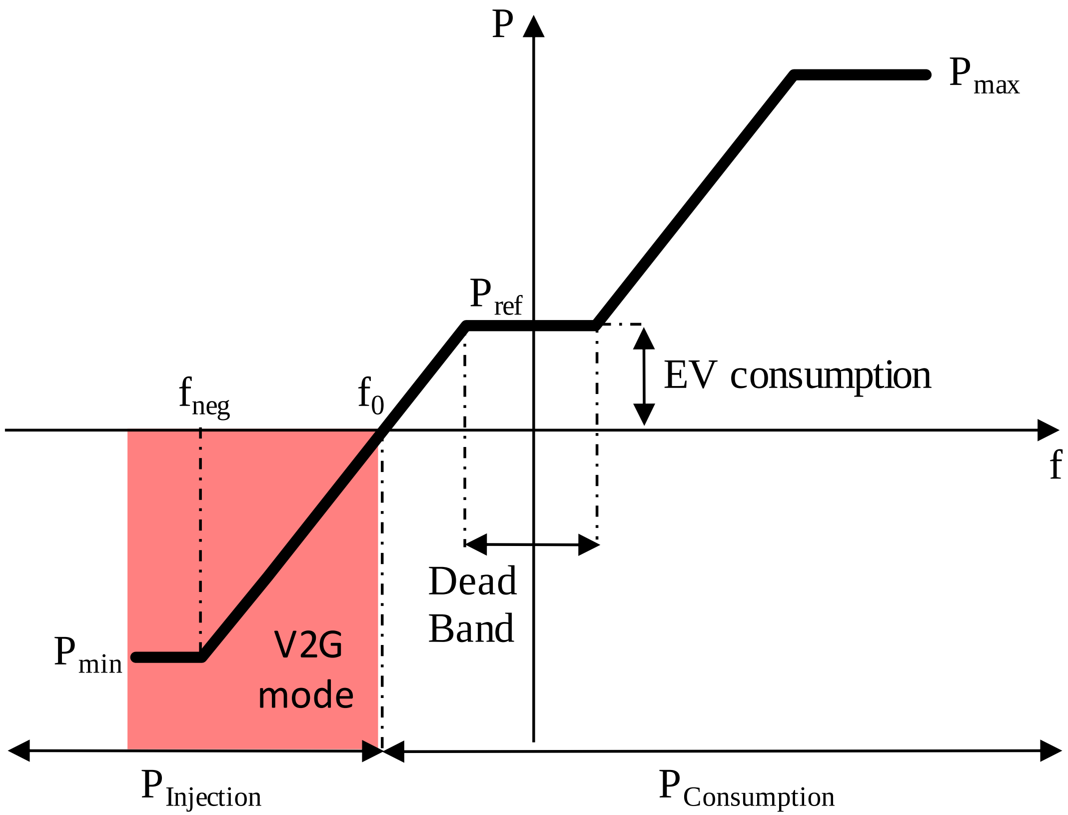
- includes an inverter allowing the connection of small wind generators up to 3 kW to Low Voltage networks
- avoids an excessive raise in voltage at the connection point
- can track frequency changes and adjust power output
- droop control principle



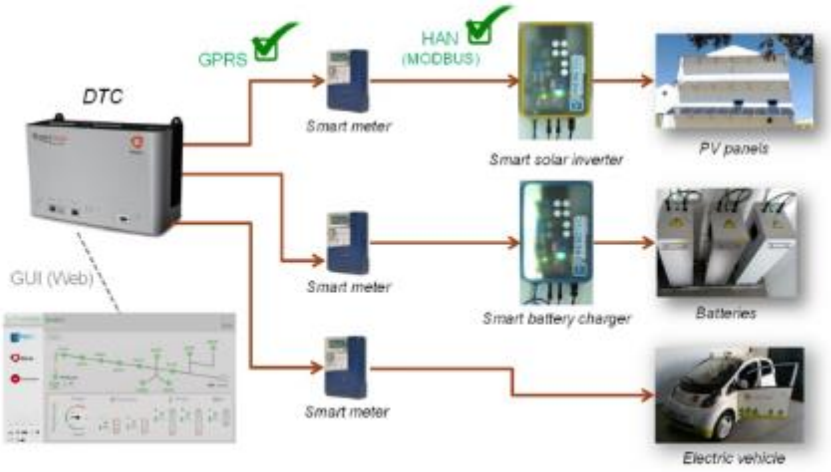
Expansion of WISE-SISE to EV – droop control

Two ways to define the reference charging power P_{ref} :

- Set-point sent by the aggregator/DSO for subscribers of Intelligent Charging
- Local decision of car owners (non-subscribers of intelligent charging)



Integrated management – a real test case



✓LV feeder with **~10% PV generation** and Smart Grid infrastructure;

✓Storage, PV Panels and EV charging **controlled by Smart Inverters and DTC;**

✓Control of DER allowed **75% reduction of curtailed Renewable Energy;**

SuSTAINABLE is a European project under the 7th Framework Programme for Research and Technological Development with contract No: 308755

AGC and local batteries with droop control – a systemic effect

Example:

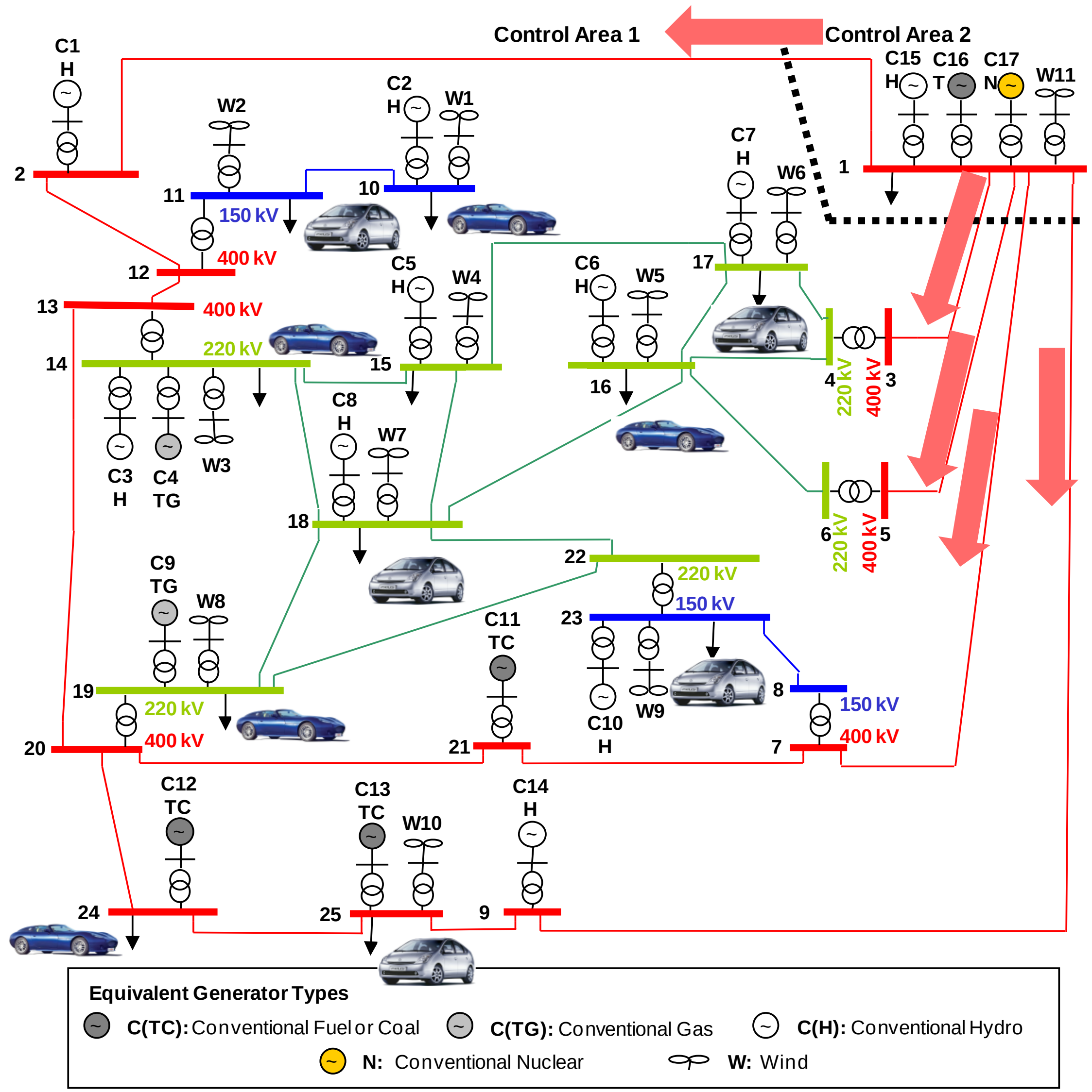
Simplified Portugal transmission grid and Spain equivalent

+

Batteries and EVs

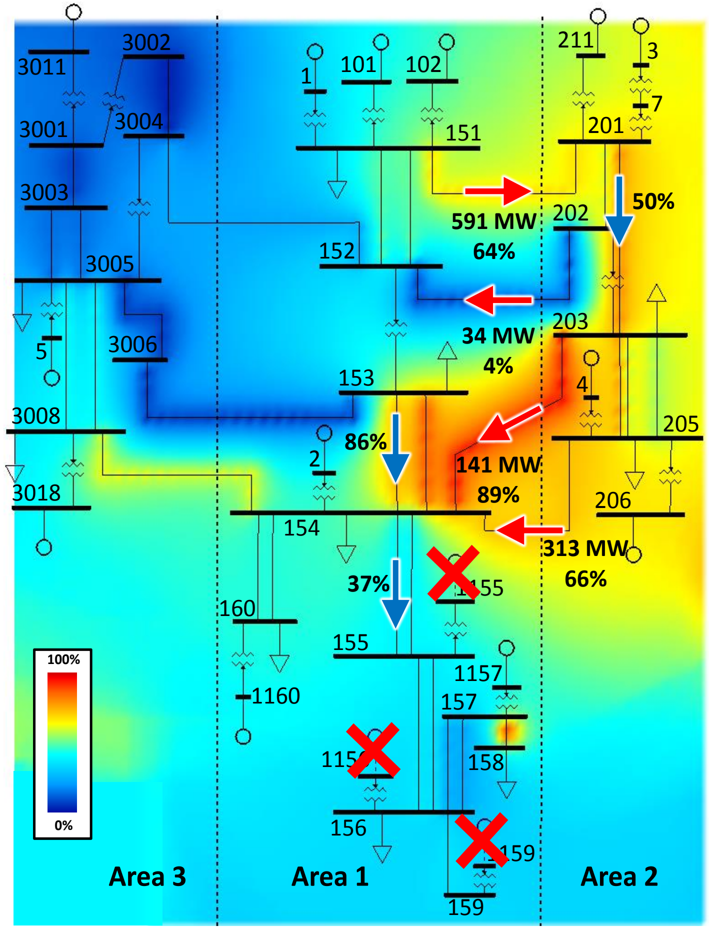
+

Chargers with droop control



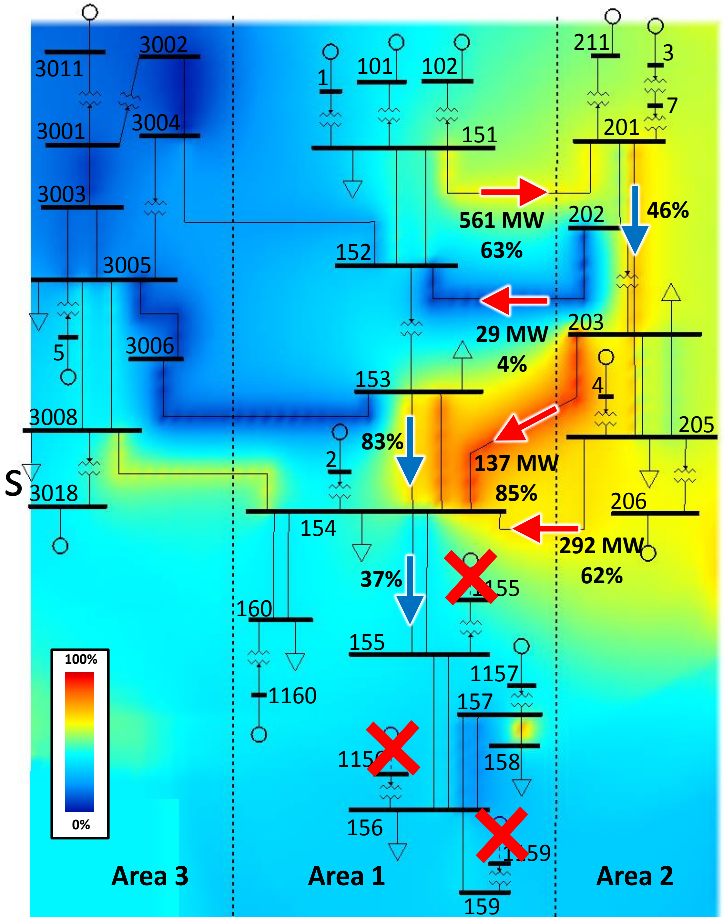
Important loss of wind generation
Flows at t = 1100 s – stress reduction

AGC w/o battery support



t = 1100 s

AGC with battery support



OLA – Observatory of Latin America

PMU connected in low voltage:

- 22 universities in Brazil
- 6 universities in Chile
- 4 universities in Argentina
- Data shipped to the Observatory in Florianópolis

Time-tagged information: like pixels in successive frames in a film

- The “film” captures the dynamics of the power system

Can we discover invariants?

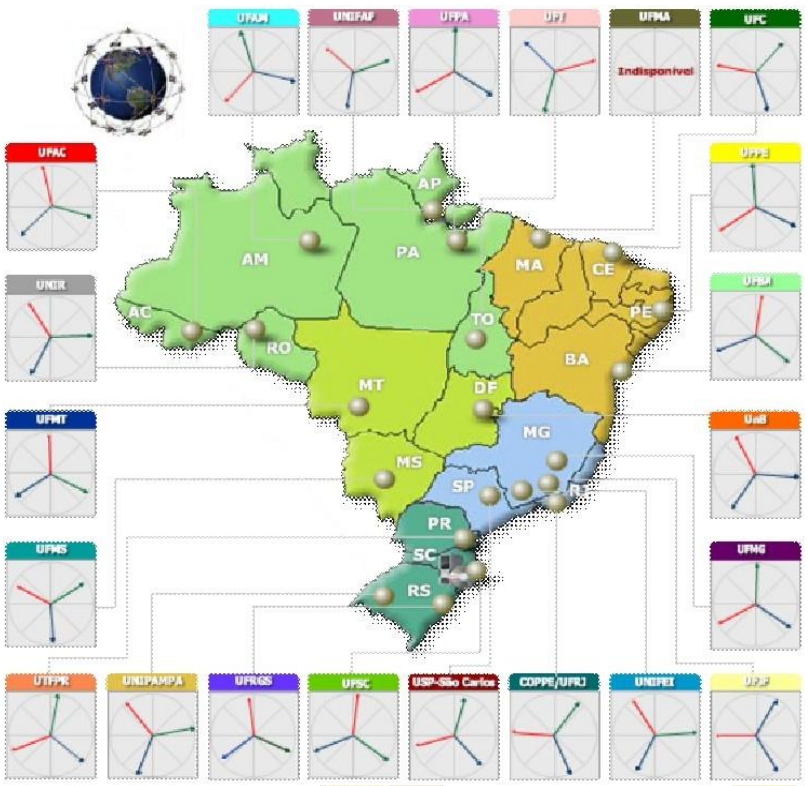
Can we build models from capturing knowledge,

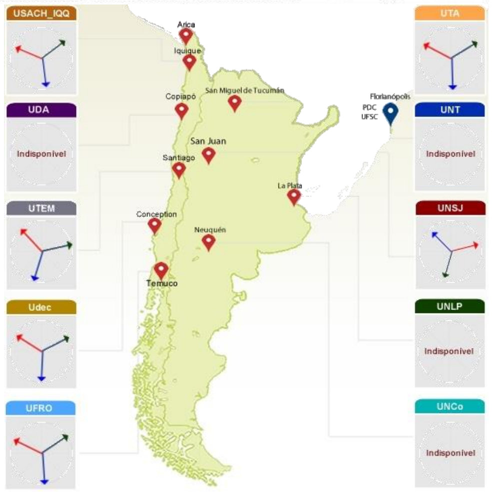
instead of from *a priori* formulations?

This project (MedFasee) is on-going in Brazil, Chile and Argentina.

http://www.medfasee.ufsc.br/temporeal/

http://www.medfasee.ufsc.br/conosur





In 2018, the Cone South of America will be covered
In 2019, Iberia will be covered

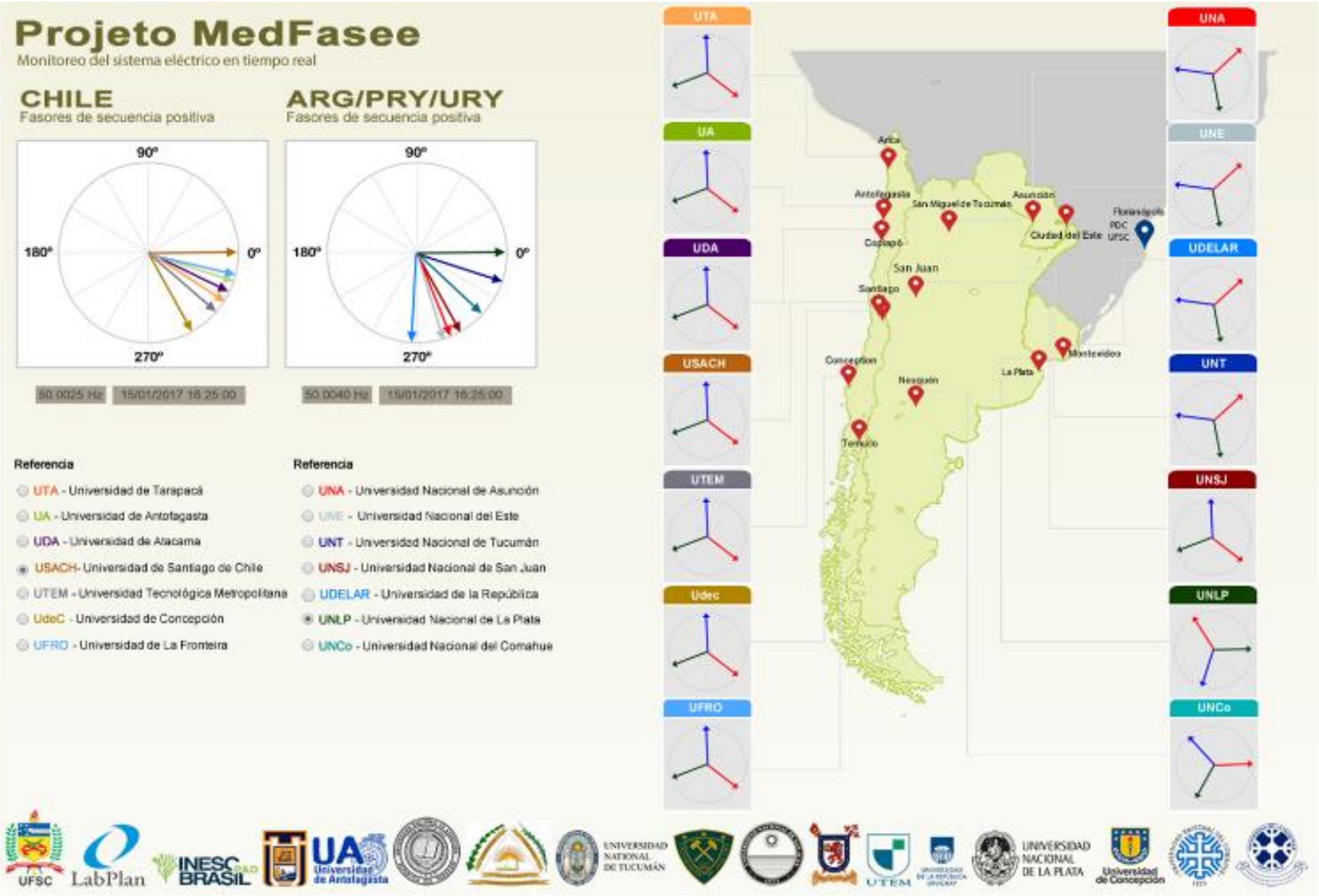
Targets beyond Brazil:

- ✓ Plan: end of 2018
- ✓ 14 measurement points
- ✓ 16 associate institutions

5 Countries:

- ✓ Brazil
- ✓ Chile;
- ✓ Argentina;
- ✓ Paraguay;
- ✓ Uruguay

Extension to Portugal/Spain: 2018/19



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Events in the Chile system: line tripping (Maintecillo: 30.May.2016)

Maintecillo – Punta Colorada 1:

- ✓ 30/05/2016 – 16h31min (UTC).

System split/disconnection, north of Maintecillo.

Estimated power curtailed:

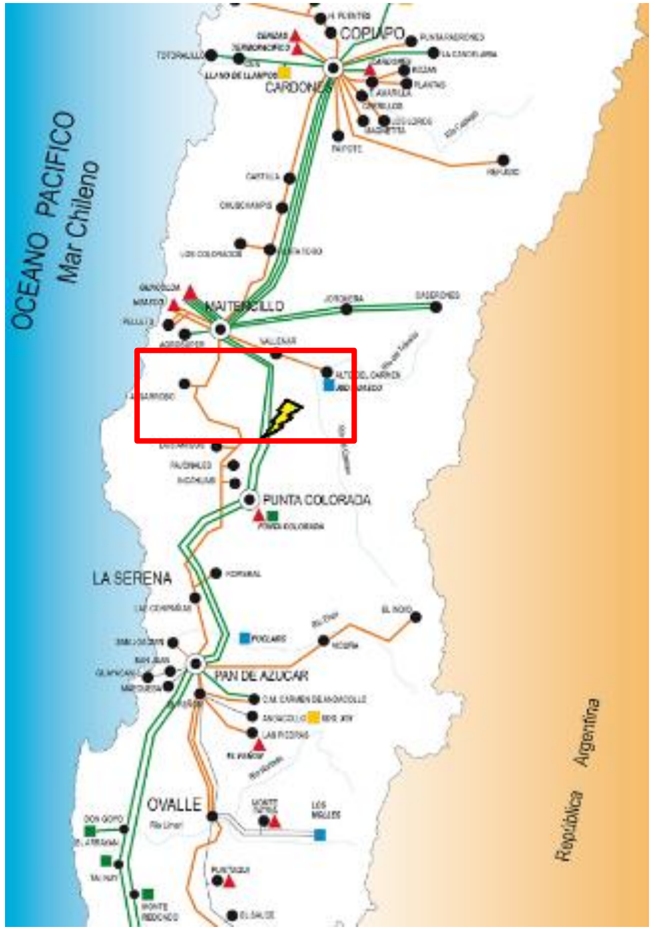
- ✓ 461 MW.

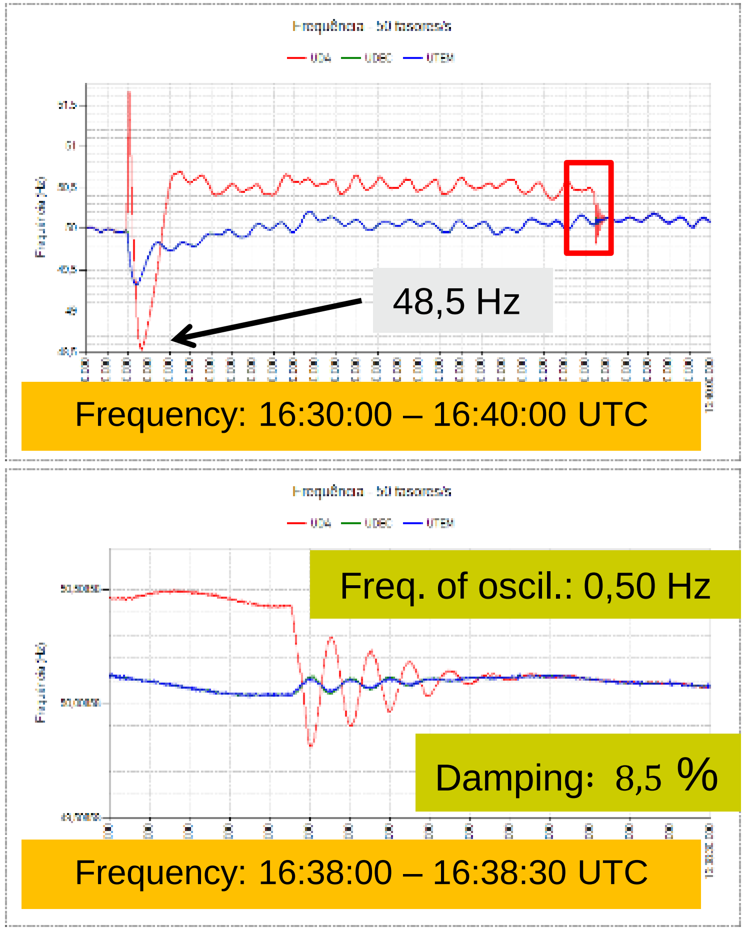
Sub-Frequency – Atacama:

- ✓ 48,5 Hz.

Recovery time:

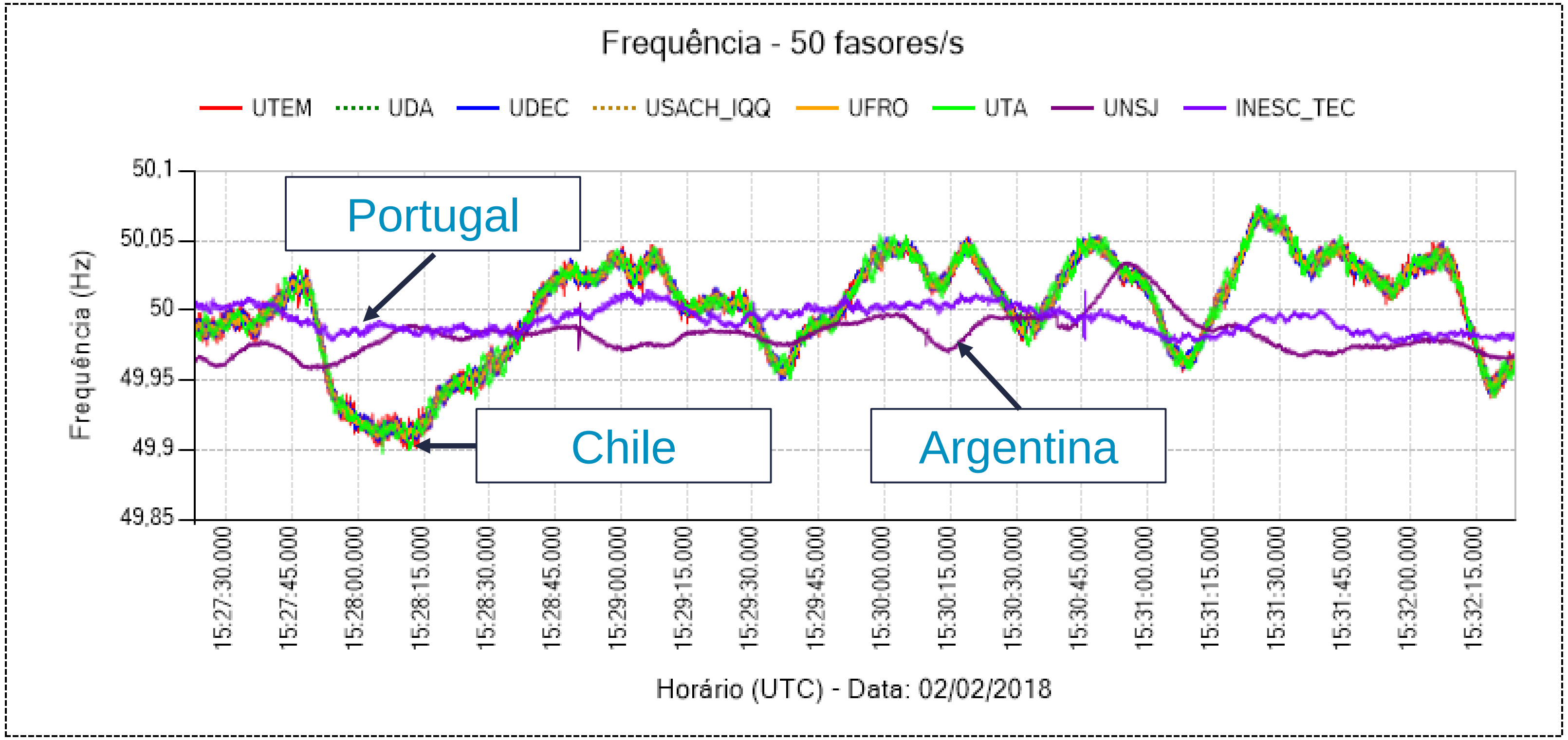
- ✓ 16h39min (UTC).





Comparison among Argentina, Chile and Portugal

The data collected in the Observatories of Latin America (OLA) and Iberia (OI) allow a comparative analysis of the behavior of different systems – and some conclusions on risk may be arrived at.



Learning: an analogy to the visual cortex

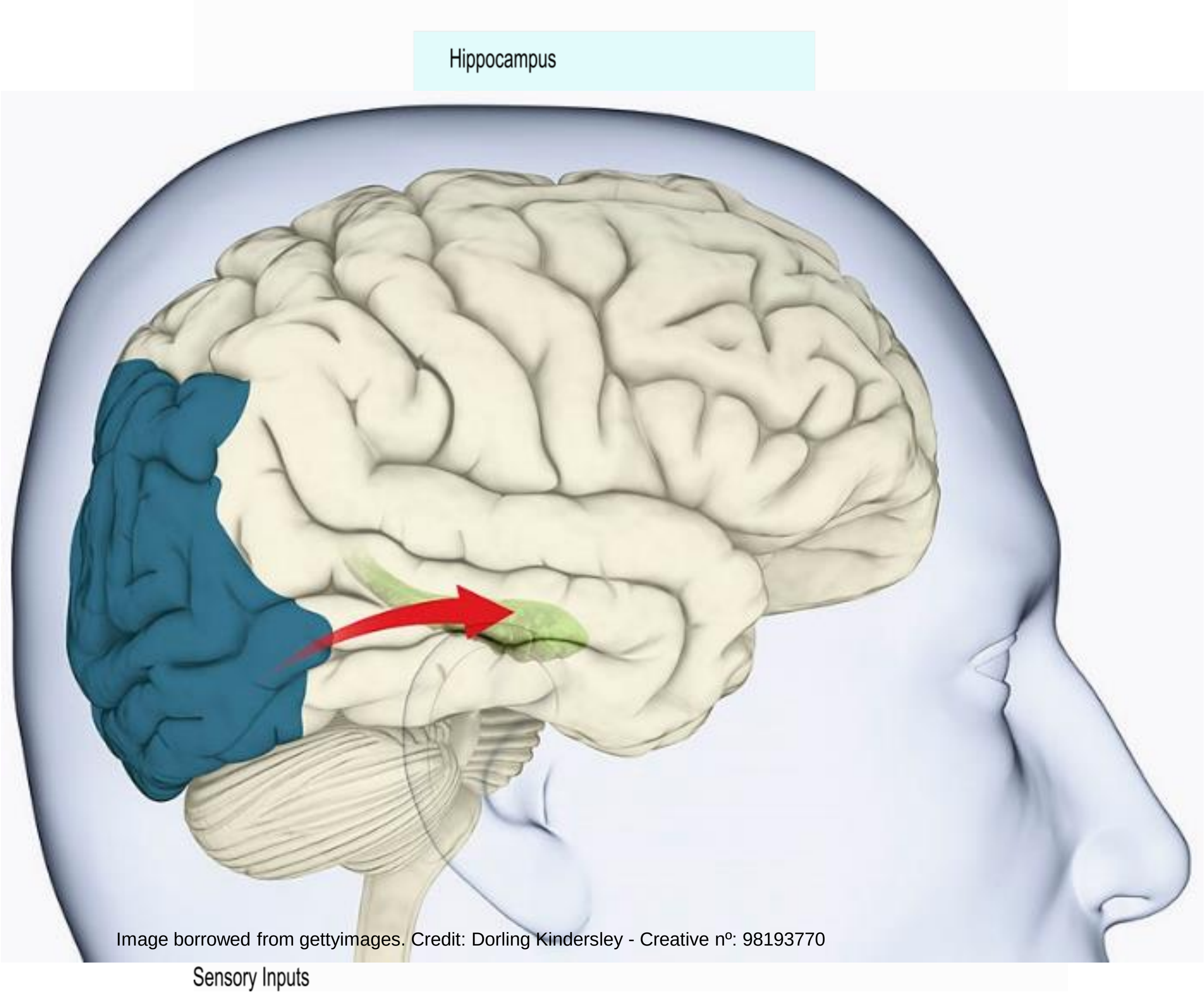


Image borrowed from gettyimages. Credit: Dorling Kindersley - Creative nº: 98193770

We share Helmholtz' view that cortical function evolved to explain sensory inputs.

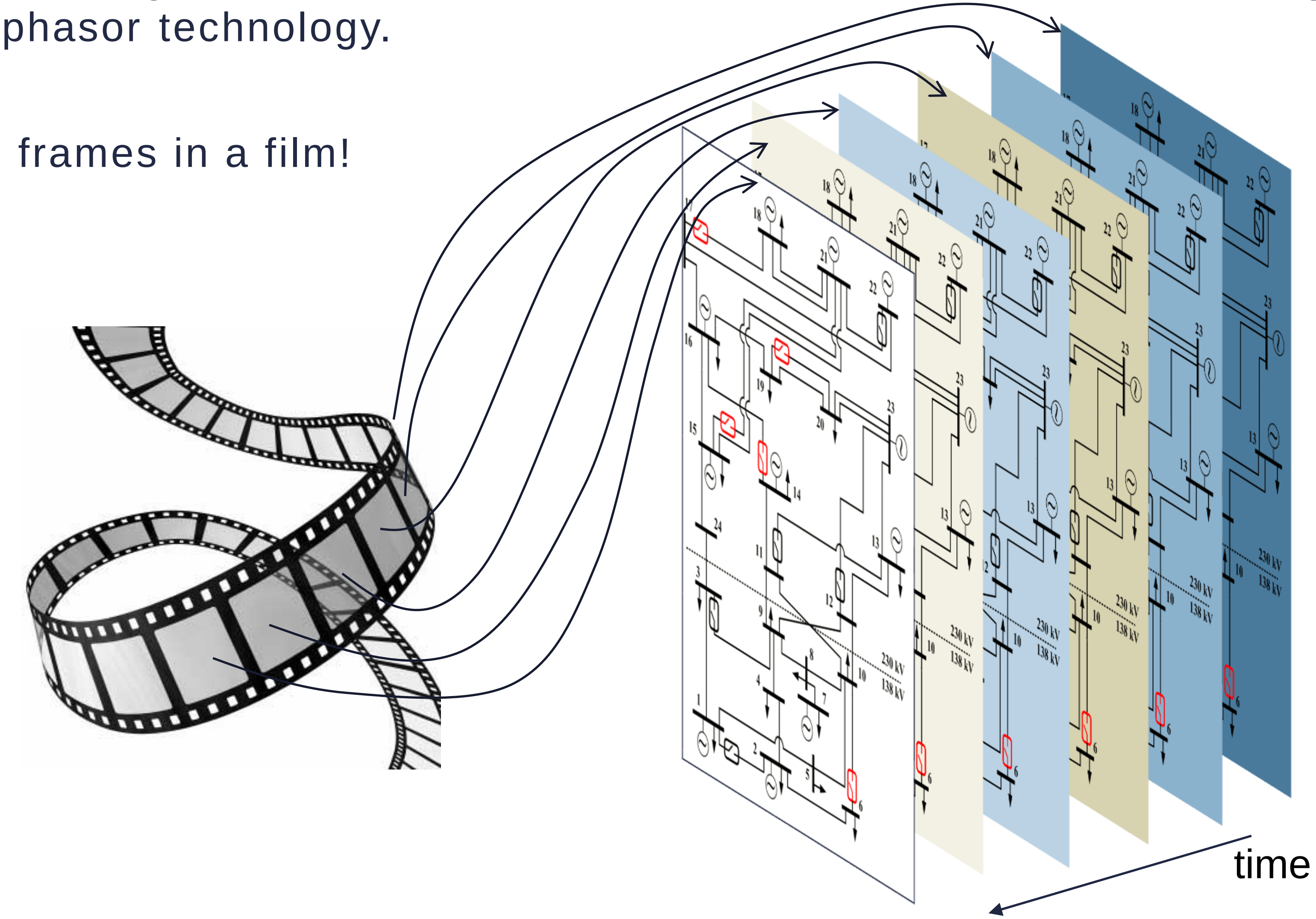
As such, we seek to understand the role of processing and stored experience in a machine learning framework for the decoding of sensory input.

(J Principe)

The continuous monitoring of a power system may now benefit from learning instead of relying on static models

All data arriving at the SCADA in a Control Center can become time-tagged with synchrophasor technology.

It is like frames in a film!



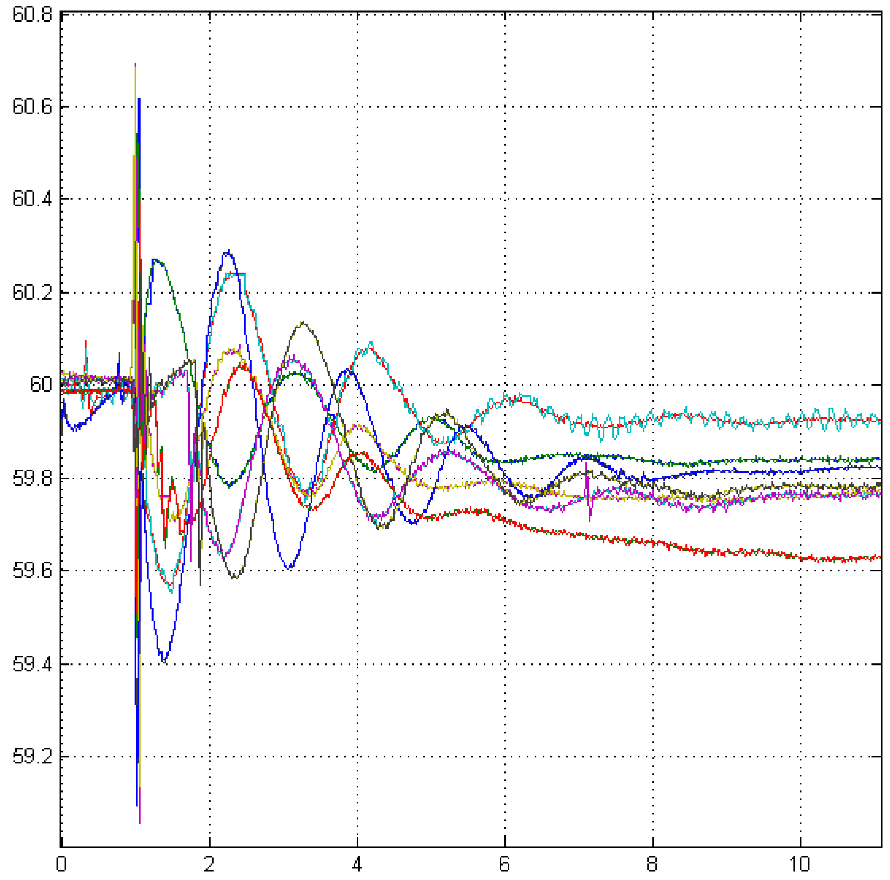
Events in the Brazilian power system

Events collected at several PMUs simultaneously

Frequency data collected at the rate of 1 measurement per 1/60 second

Examples of events stored in the time-tagged database, in 20 seconds long patches (1200 measurements per PMU) – 1 second before and 19 seconds after:

- Generator tripping
- Line tripping
- Load shedding
- Oscillation



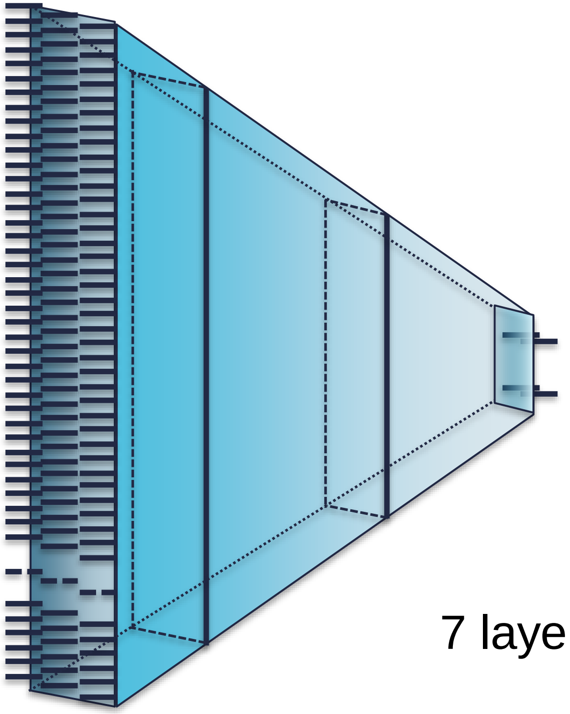
INESCTEC

New models tested
Convolution Neural Networks

Deeper networks with 4 outputs (1 per event)

0	1
0	0

CNNs mimic the neural structure of the visual cortex



7 layers

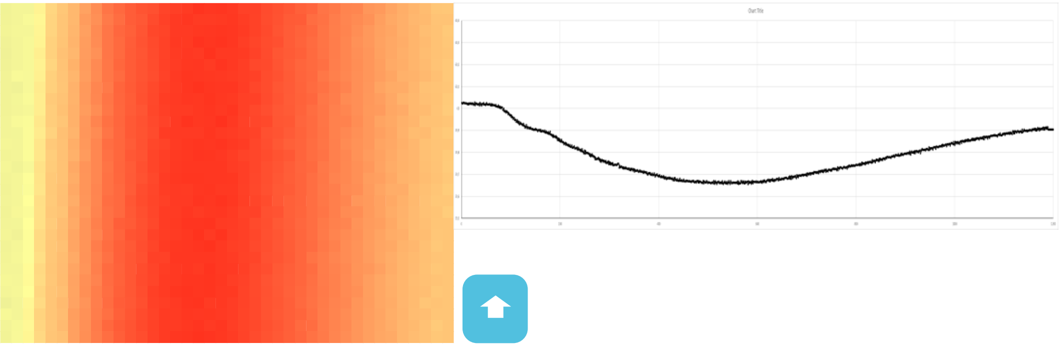
Experiments:

frames of	1 x 1200	5 x 240	
	2 x 600	10 x 120	
	3 x 400	20 x 60	
	4 x 300	30 x 40	pixels

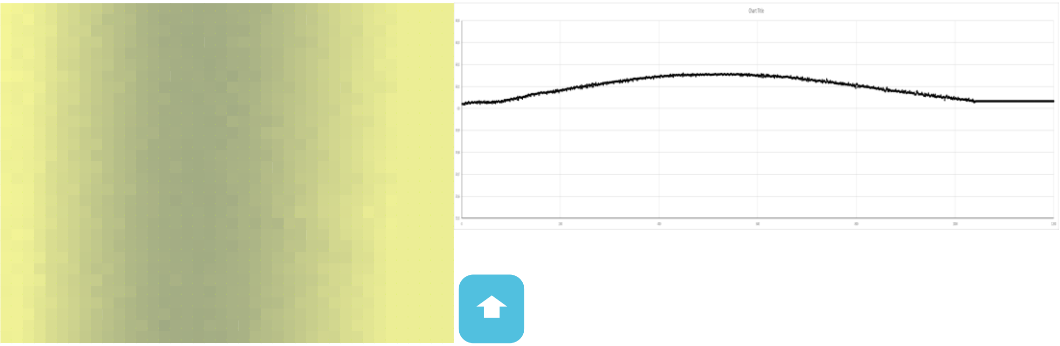
inputs are treated as images!

Events in the time domain
perceived as images

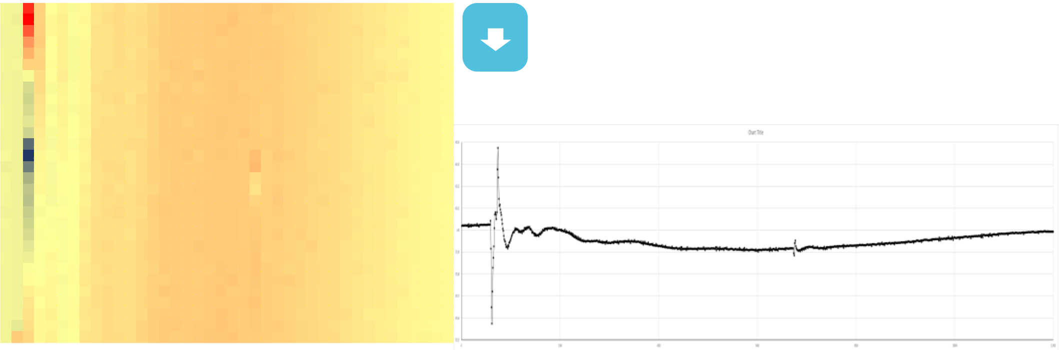
Generator tripping



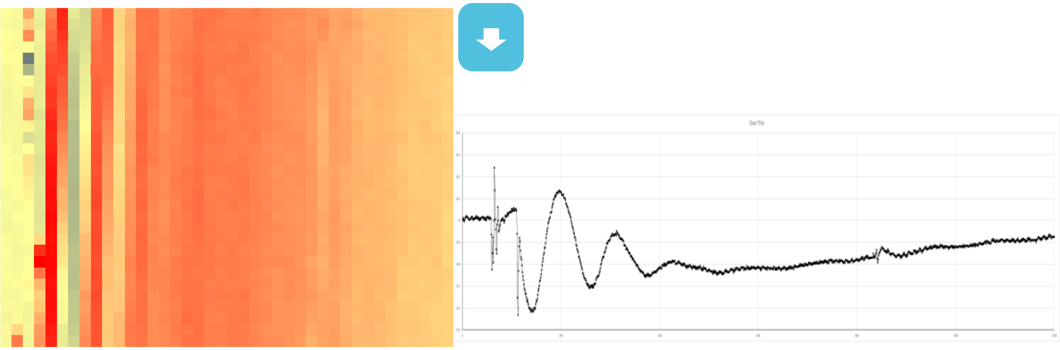
Load shedding



Line tripping

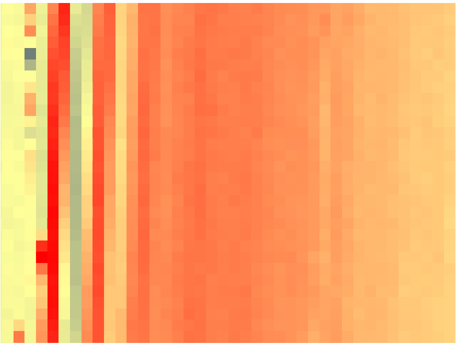


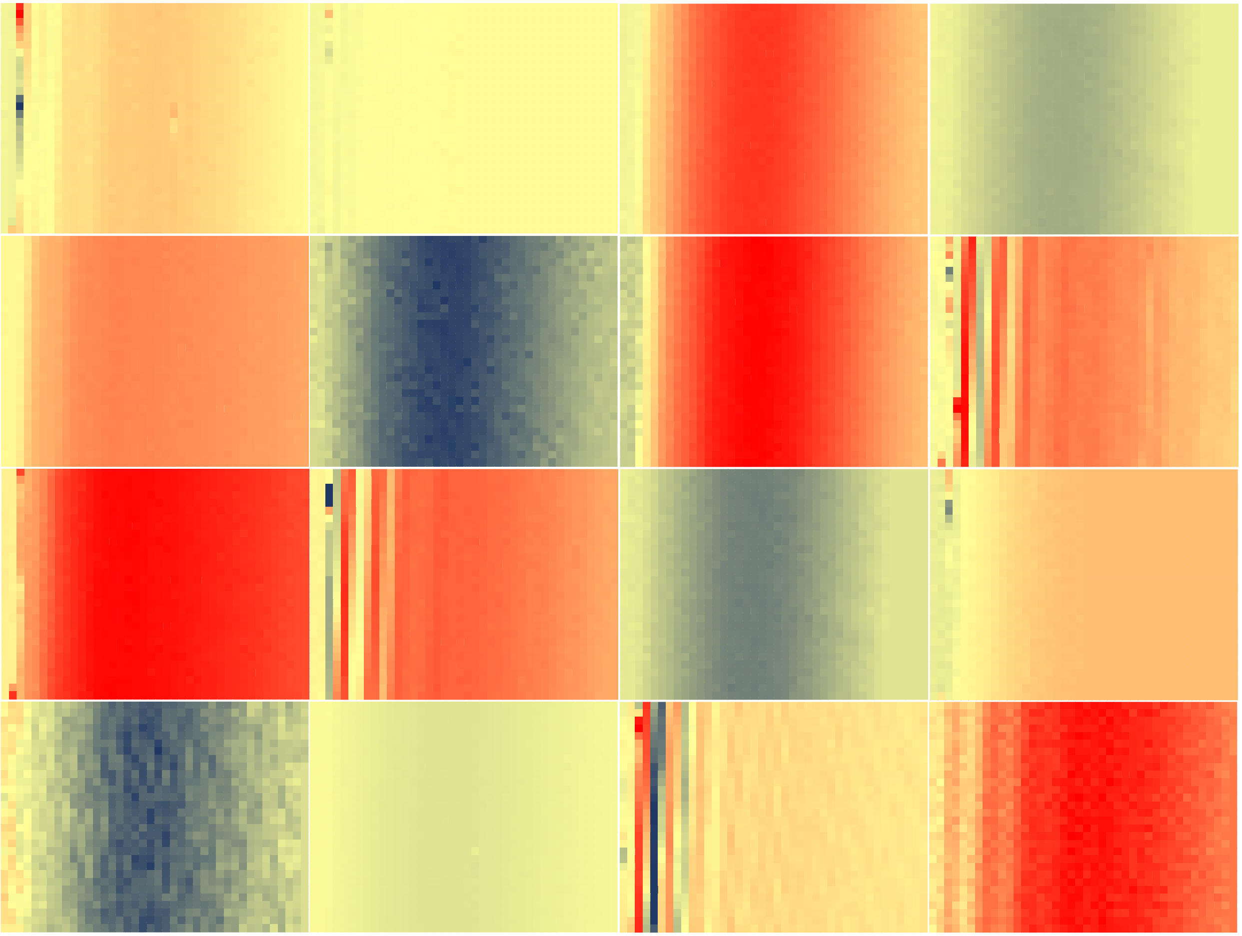
Oscillation



Look: can you see?

Gelöseatidiptinging





The analogy with the visual cortex is powerful

The convolutional neural networks, with an architecture inspired in the visual cortex, and with the input sequences organized as rectangular movie frames, were 100% successful in identifying the 4 events, from a pool of events presented to the network!

model	error in event recognition
Deeper Feedforward ANN	1,5 %
Deep Belief Networks	1,5 %
Convolutional Neural Networks 30x40	**0 %**

Frames	1x1200	2x600	3x400	4x300	5x240	10x120	20x60	30x40
Erro	4.76%	2.34%	2.47%	1.15%	2.22%	1.48%	0.49%	0 %

These promising results in recognizing events are inspiring!

The visual cortex architecture recognized features that other architectures could not

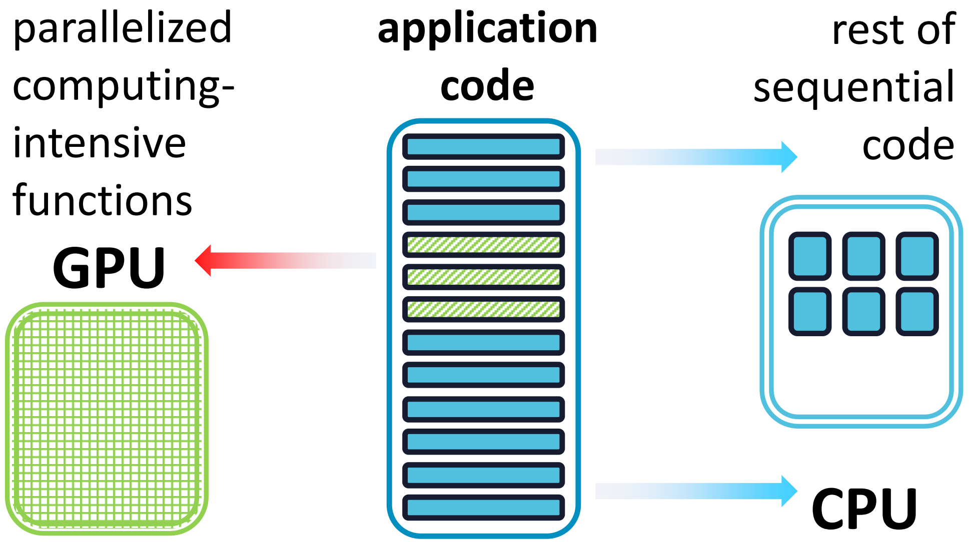
The events representing inter-area oscillation (OS) were very difficult to correctly identify with all models – except with the CNN

	MLP1	MLP4	MLP8	DBN	CNN2	CNN3
no. errors	3	3	3	3	1	0
mistakenly labeled events	GT GT LS	GT GT GT	GT GT LT	GT GT GT	GT	-
correct event identification	OS OS OS	OS OS OS	OS OS OS	OS OS OS	LT	-

These promising results in recognizing events are inspiring!

GPUs bring strong acceleration to the deep learning process

Graphics Processing Units may have thousands of processors and allow parallelization of algorithms

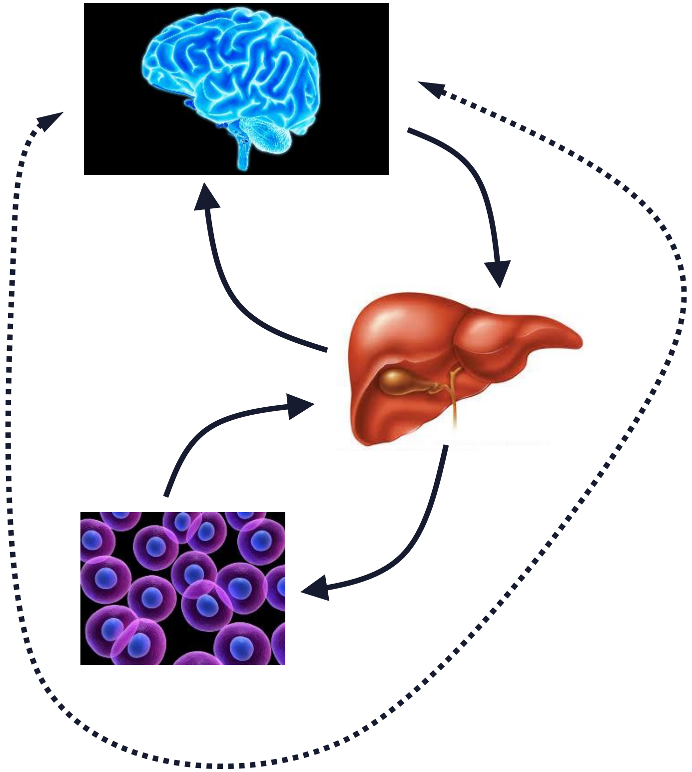


For the CNN3 (30x40 pixel frames), treating 1357 events from the Brazil PMU data base, the time needed with GPU was of 16.5 seconds (with CPU only, 7,5 minutes).

	MLP1	MLP4	MLP8	DBN	CNN2	CNN3
speed-up GPU/CPU	3.6	4.1	8.1	8.8	31.6	27.2

Towards OOPS! – the organically organized power system

The biologic metaphor is growingly appropriate: nested control systems and differenced missions at distinct hierarchical levels.



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