Automation of Energy Systems

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Introduction

- Course *rationale* and overview
- A few words on history
- Some bare essential definitions
- A first glance at control problems
- Recap, needs and next steps

Foreword

(more automation needed for increasing complexity)

- Systems that produce, distribute and use energy are becoming more and more complex and articulated:
  lot of new energy problem / opportunity
  - different sources (renewable or not);
  - different types of generation (e.g., centralised vs. distributed);
  - complex markets in rapid evolution;
  - ...
- Therefore, energy system experience an increasing need for automation
  - at more and more levels (from the power plant to the town grid, down to the single house); → now more syst
  - more and more integrated (e.g., to coordinate the generation and use of electricity and heat);
  - and for new demands (comfort, economy, environmental impact,...).

↑ new scenario

Foreword

complex scenario... we look on system P.O.V, NOT on mechanism ecc...

- Purpose of the course:
  - address the *scenario* just sketched
    - providing the student with a *system-level* view – typical of the Automation Engineer – on the encountered control problems, the solutions adopted for them to date, and the possible future developments
    - avoiding details on the various types of generators, utilisers and so forth—a matter to which specialised courses are devoted.
- *Caveat emptor*:
  - an exhaustive treatise of the matter is absolutely impossible, even at quite high and abstracted a level;
  - thus we shall proceed by introducing general concepts and then going through illustrative examples and cases; from general idea
  - it will be the duty of *you engineers* to abstract, the lessons learnt, generalise and transpose the underlying concepts where applicable.

Where is automation in energy systems?

simple examples: "PROCUMER")

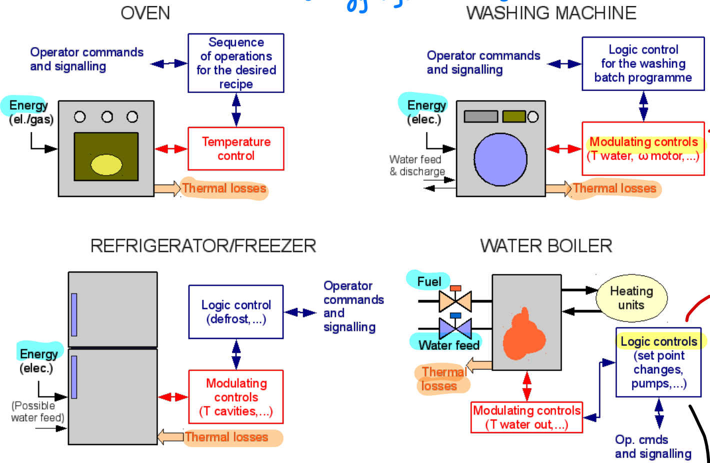
using energy efficiently (PRODUCER + CONSUMER)

Let us analyse some introductory schemes

energy syst deeply connected to others

producer @ home like with photov. or reducing consumption

Input on syst



when output is a Real number, like in a PID

(ON/OFF) output as logic variable

system ↔ use/produce energy

set point changes to disturbance

Where is automation in energy systems?

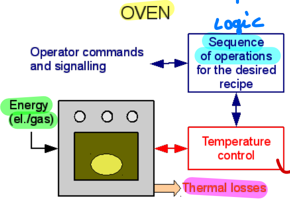
(understand problem)

Let us analyse some introductory schemes

here we deal with small energy system. → using energy efficiency (OR for destruction)

INPUT on syst

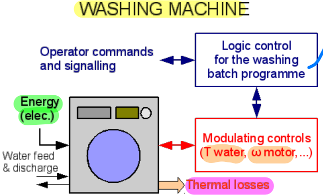
losses



shut down

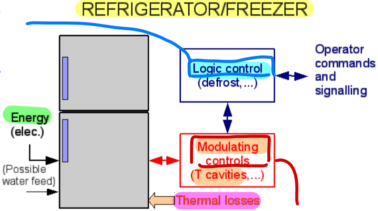
logic

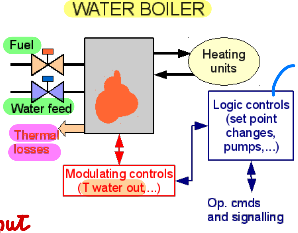
modul.



programm for washing

when output are lexical variable like ON/OFF STOP/FORW/BACK ... → Logic





different set up of syst.

when output of controllers are Re number (like PID)

Where is automation in energy systems?

A bit of generalisation

- Carrying on with the list:
  - generators (fossil, hydro, solar, wind, geothermal,...);
  - other "utilisers" (heating elements, fan coils, AHUs,...); Air .. Units
  - maybe some home/building automation, not installed (only) for energy purposes... ...but surely with a relevant energy effect;
  - ...

from MICRO scale.

- Scaling up:
  - "larger" components (building or compound-level HVAC,...); (heating, Ventilation, Air conditioning)
  - industrial machines/installations;
  - large power plants;
  - ...

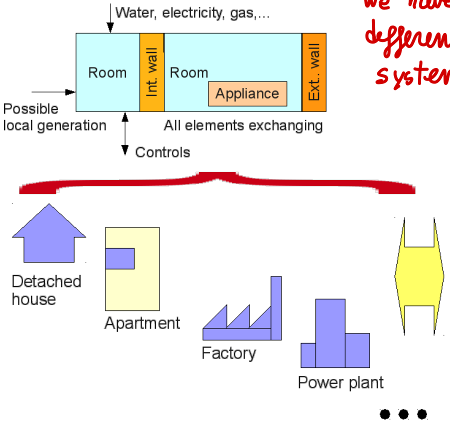
using energy for some purpose and control is BIG

Where is automation in energy systems?

Let us now start *aggregating* ↓ all elements exchange energy in between

we have exchanges of different energy between systems (entity)

each entity can be house / power plant.. interconnected as huge syst overall ↓



all energy syst interconnected

NETWORKS

electricity,
water,
gas,
...

NOTE: each part of the system has its own controls, and must somehow coordinate with the others. !

Summing up...

(like set of machine)

- Each object (or aggregate of objects) is generally controlled for *local* goals:
  - cook some food as quickly as possible;
  - maximise the economic revenue of a household photovoltaic generator based on forecasts of weather, energy use and prices of electricity and gas;
  - generate the total power required at any time by the national network while maintaining each plant as close as possible to its optimal operating point and without overloading the transmission lines;...) ↳ balance the summ of powers to match demanding

(working optimal.)

- bearing however in mind that any action on that individual object will (more or less) influence the overall system. !

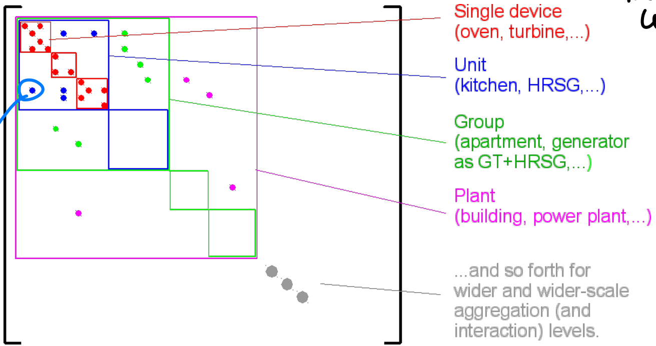
Is there any *hierarchy* in energy systems?

↪ peripheral / plant level... different level of control, you have hierarchy?

- Rigorously, no. ↵ • everything seems coupled! ⇒ No hierarchy
- To understand, let us fictitiously imagine to write the whole dynamic model of the "world" energy system and observe its *incidence matrix* (a boolean matrix showing which variables appear in which equations): ↓

block diag structure with some off diag elements

state equations :



true if a certain var appear on one equation..

some exchange between

--- Variables

Is there any *hierarchy* in energy systems?

for hierarchical syst you have different controller level

variables

$$\left[\begin{array}{cccccc} 1 & 0 & 1 & 0 & - & - \\ & - & - & & & \end{array}\right]$$

equations

Bool Matrix

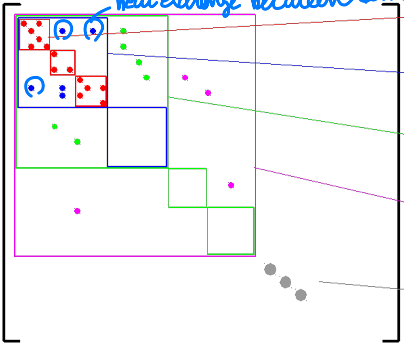
1 if var appear on eq, 0 otherwise

- Rigorously, no.

in fact

- To understand, let us fictitiously imagine to write the whole dynamic model of the "world" energy system and observe its *incidence matrix* (a boolean matrix showing which variables appear in which equations):

heat exchange between device



they exchange heat through environment

room exchange with the home

apparently huge sparse matrix, small influence in between diff. syst.

Rigorously all is coupled

we want to simplify! introduce hierarchy by structuring model

However, structuring is needed

hard!

- Apparently, the problem needs *decentralised* solutions — at far smaller scale than the planet ☺
- ⇒ Therefore, some hierarchy - or better, as we shall see, some *structuring* of the problems is in order. ← approx needed to approach syst
- In other words, we need

  depending on applications

  face problems general one by one
  - to understand which are the relevant problems (a task already carried out, although the matter is continuously evolving, think e.g. of environmental issues)
  - and that can reasonably be dominated (which is often not trivial),
  - find for them solution that are sound from an engineering standpoint
  - and figure out how to put said solutions at work also when the boundary conditions for the problem at hand vary, which can also be due to how the *rest* of the system is affected by the introduced solutions.

Consequences

if for ex. I wanna control an obj Temp Q Q Influence ext temp.

its boundaries Temp is a boundary condition OR I need to care about Q exchange

With many interacting syst, a Boundary condition is something which does NOT depend on me → not influenced

so by matrix ecc...

- What do we mean "a problem can be dominated"?
- Essentially that once said problem is stated in system-theoretical terms
  - having extended its size (i.e., the set of described phenomena) enough for the "rest of the world" to be properly represented by boundary conditions and/or disturbances (i.e., exogenous entities)
  - it is possible to find for it a solution of acceptable complexity and implementable with information available in practice.
- An important concept in this regard is that of "dynamic separation", on which we shall return in due time.

an object influence its boundaries...
the boundaries condition depends on how the syst works → understand problem and approach it as control

"bounderies condition" when DON'T depend on me → known,
it can depends on interaction outside

ROOM a | ROOM b

T_a | wall | T_b

≃adiabatic

is $\underbrace{T_a \simeq T_b}$
adiabatic wall, NO Q exchange
because the 2 Rooms are controlled

understand ↙
the problem to know how to connect blocks → using dynamic sep.

Consequences

[use a given model of the syst depend. on complexity] ⇐ (Model is important for control)

control problem thinking

- To state and address problems this way, we need a "systemic" approach, in which components
  - can be described at different detail levels, (the model to use depend on the application)
  - but preserving their interfaces with other components of the overall system,
  - and as independently as possible of how they are connected to the rest of the system;
- at the same time, the approach should allow to state problems in such a way to be tractable with well established control methodologies and techniques (although the energy context has been fostering new ones).
- In addition, simulation techniques play a crucial role.

Coverage

— or, “where is automation” revisited in a more strict sense

↳ in large energy SYSTEM

energy system ?

Controlled "system of systems":
producers, utilisers, storage, transport networks...

Coverage

— or, "where is automation" revisited in a more strict sense

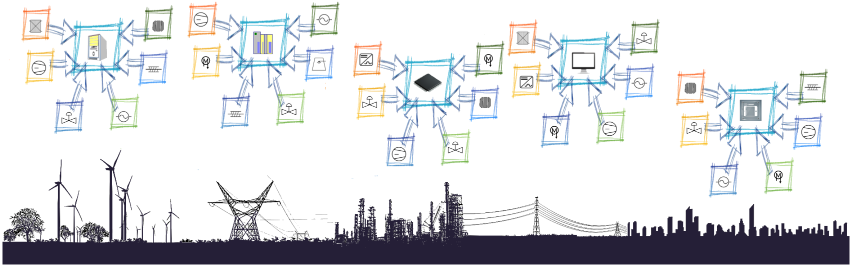
control scheme such that disturb / uncertain are killed
(near origin ≃ 0)

pressure, flow,
temp., voltage,
freq...

(above the systems)

to manage individual unit

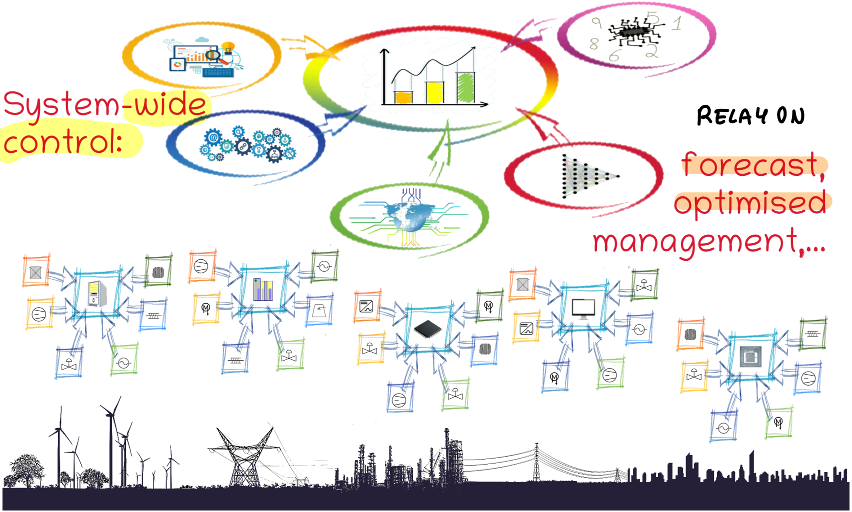
Modulating loops & logic at "peripheral" level:
unit management, response to local events,...



Coverage

— or, "where is automation" revisited in a more strict sense

System-wide control:



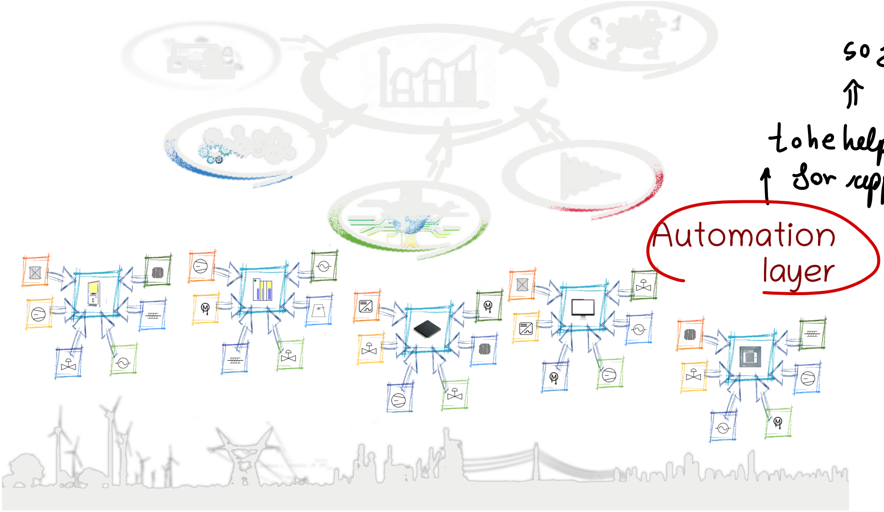
forecast, optimised management,...

RELAY ON

on top

Coverage

— or, "where is automation" revisited in a more strict sense



so for optimiz.
⇑ level

to be helpfull
↑ for upper level

we deal
with Aut.
Layer

An automation layer as a contributor to "smartness"

— i.e., an important aspect of our focus

- **Wikipedia**
  Smart systems incorporate functions of sensing, actuation, and control in order to describe and analyse a situation, and make decisions based on the available data in a predictive or adaptive manner, thereby performing smart actions. In most cases the "smartness" of the system can be attributed to autonomous operation based on closed loop control, energy efficiency, and networking capabilities.

$\Downarrow$

- Make thus local- and mid-level controls efficient, and as a consequence
  - local events will be managed locally instead of scaling up to involve system-wide controls,
  - so that the said controla will see a "simpler" managed object
  - to the advantage of operation optimality.

↑ manage locally

A few words on history

- How has automation in energy systems developed?
- Initially (and trivially) to be able to run them: without control systems one can
  - neither operate a power plant
  - nor avoid the electric network collapse
  - nor maintain the required pressures in a gas network extending for tens of thousands of kilometers; ← large syst.

some losses are inevitable, but can be improved

- then (and by the way almost immediately) for efficiency reasons concerning "big" system components (e.g., power plants), which self consumes 10/15% of overall generated
- but always having in mind, more or less explicitly, a fairly well defined structure of the system (in the electric case, for example, a few large generators, transmission, distribution, and many utilisers of variable size but small if compared to the generators).

less generator than loads

↑ OLD situation of Energy Syst

A few words on history

Today scenario!

- Today, however, the *scenario* has changed:
  - there is more and more distributed generation to be integrated with the network,
  - different energy sources, both renewable and not, are being considered,
  - economies of scale are being exploited (think e.g. of district heating), → one more efficient
  - integration is spreading out among controls (e.g., feedforward compensation from heat-releasing appliances to room temperature controllers)...
  - and sometimes among "machines" (e.g., heat recovery, generation surplus management, and so forth).

Summing up...

• old paradigm still used

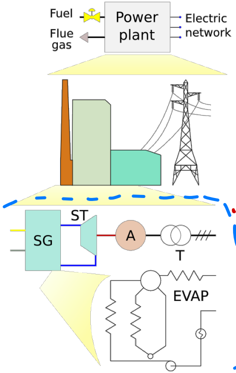
- Energy systems provide a number of control problems to address, and several are "new".
- Many solutions that were acceptable in the past are no longer acceptable today (efficiency demands are becoming more stringent).
- In the course are we thinking to address everything we have mentioned so far?
- Not at all: it would take too long and would not even be a "smart" idea.
- Let us therefore review the initial statement about the purpose of the course as we can now give it a more precise meaning...

Summing up...

...by means of another scheme

see power plant as a Box, with gas flue Input and electr. netw output
(our interest!)

(1) Complex models, typically object-oriented, for component-level studies

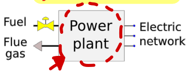


Up to many thousands of equations and state variables

inside syst you have many sub-syst.

different topology

(2) Simple models, typically object-oriented, for system-level studies



Up to around ten equations and state variables

I/O control

(3) Simple models, typically block-oriented, for control synthesis

Generally not more than four-five equations and state variables

complex obj-oriented systems connected not just by I/O but with connecting objects Box model like a WIRING.. assembling with CONNECTIONS

- (1) and (2) have the same interfaces;
- (1–3) must be consistent; (1-2-3) consistent
- in this course we concentrate on (2–3) and only sketch out relationships with (1).

environment model to face it simple

Course organisation

General information

- The course consists of
  - about 30 hours of lectures
  - and about 20 hours of classroom practice, including some computer laboratory activity,

  for a total of 5 CFU.
- Lectures are guided with slides,
- while classroom practice/laboratory involves guidance as well as individual work.

Course organisation

Synopsis of lecture and practice subjects

- Introduction (this lecture);
- review of the mathematical, modelling and control principles that will be used later on;
- the main physical objects (generators, utilisers, distribution networks) involved in energy systems:
  - synthetic description and dynamic behaviour in the context where they operate,
  - simple models, parametrisable with the minimum necessary information;
- the main control problems in energy systems and the strategies to handle them.

Classroom practice sessions, interlaced with lectures, contain examples and case studies concerning small applications, and involve the use of open source simulation and control synthesis tools.

Instructor information, online resources, contacts

- Alberto Leva
  Dipartimento di Elettronica, Informazione e Bioingegneria
  Politecnico di Milano
  Voice (39) 02 2399 3410
  E-mail `alberto.leva@polimi.it`

- Resources:
  - course page on WeBeep (`https://webeep.polimi.it`, course ID NNNNNN),
  - git repository at
    `https://github.com/looms-polimi/Automation_of_Energy_Systems`,
  - old web page at `https://leva.faculty.polimi.it` → Teaching.

- Office hours:
  - at the DEIB (2nd floor, room 234) on Monday, 14.30 to 16.30,
  - or by appointment.

Teaching material

- Course slides (*in fieri*);
- some literature and web references, that will be introduced later on.

Software

All free (as free speech, not free beer)

- **Scilab**:
  analysis, synthesis and simulation of causal dynamic systems (block-oriented approach).
  `https://www.scilab.org`
- **OpenModelica**:
  modelling and simulation allowing for a-causal components (object-oriented approach).
  `https://www.openmodelica.org`
- **wxMaxima**:
  CAS (Computer Algebra System) for symbolic computations.
  `https://wxmaxima-developers.github.io/wxmaxima`

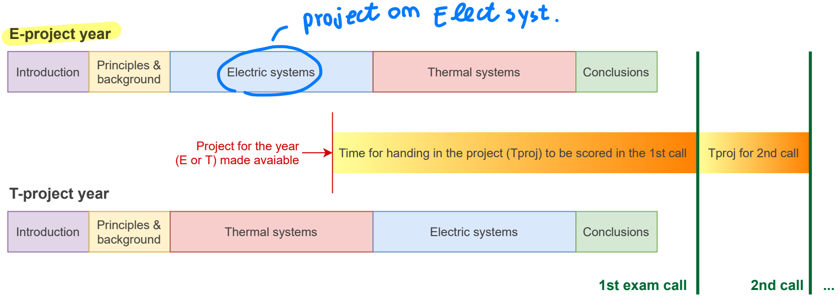
- **Important note**: the goal of this course is not to teach (let alone compare) approaches to modelling and simulation, nor is it to train students for the use of one or another software; the applications above are *only* tools for putting the concepts learnt to work.

Exam

- The exam is made of a project and a written test.
- The project is scored 18–30L (33) and contributes 40% of the total score.
- The remaining 60% comes from the written test (approx. 1h30").
- The written test is scored up to 30L (33) as well.
- To pass the exam, the written test score must be 16/30 or above; lower scores cannot be compensated for by the project.
- You can hand in the project only once; no exceptions.
- If you re-enroll to the course for another year, the project is still valid.
- On the other hand you can repeat the test as many times as you wish (*cum grano salis*, please).
- But starting – not handing in, beware – a written test, erases any previous test score.

Exam

- You must hand in the project before taking the written test.
- To make this feasible, thanks to some modularity in the course, the timeline is as follows (box widths are not to scale with time):



- E-project and T-project years alternate. This year is E-project.
- The written test is always on the entire course.
- The project theme (electric or thermal) changes every year — yes the project score is valid forever anyway, to prevent useless questions ☺

Exam

- For the project, you have to form teams of four.
- You will solve an energy-related automation problem, of reasonable size and complexity, using the methods and tools taught in the course.
- You will then create a slide-based screencast (maximum 15 minutes, sharp) to show your results; the presentation structure is totally free and up to the team.
- Only two constraints (for a motivation, search "pitch presentation rules"):
  1. all members of the team must talk, no matter order and distribution;
  2. at 15 minutes from the start I stop the player, whatever comes after does not exist.
- You will finally pack the screencast, the slides and the required code (details in due course) into a single compressed file, and deliver this via BeeP.
- Clarity and presentation quality will be taken into account in the evaluation process — I do not mind a lot about *video* quality as long as I can understand, though.
- In the event of significant doubts, I might ask for a colloquium with a team (arranged on a per-case basis).

Exam

Privacy note — pedantic but required, apologies

- We are managing project groups by means of a shared worksheet on OneDrive.
- Access will be possible only by authenticating with the polimi online services.
- This means sharing your name, registration No. and `@polimi` e-mail with the class.
- No project evaluation is ever shared (outside the team).

- If you object to the above, please send me an e-mail: silence for one week starting today will be taken as "all right, I am fine with this".
- Objecting persons – hopefully few, but feel free – will be managed separately (as said intra-team info sharing is inevitable, however).
- And now, let us begin the course.

Energy sources classification

- **Primary – Secondary Energy (PE–SE)**
  - Primary energy is that gathered directly in nature:
    coal, oil, natural gas, biomass, radioactive substances, geothermal energy, wind, sun radiation, gravitational potential energy (e.g. for hydroelectric generation),...
  - Secondary energy is obtained by transforming primary energy in a form easier to use/store/transmit:
    electricity, fossil fuels, hydrogen, steam...
- **Renewable – Non Renewable Energy Sources (RES–NRES)**
  - Renewable energy is obtained from (practically) inexhaustible sources (and without pollutant release):
    sun, wind, tides, geothermal heat,...
  - Non renewable energy implies consuming some "fuel" (and releasing some pollutant):
    fossil fuels,...

$\Rightarrow$ Extracting, transforming and transmitting energy are industrial processes where automation is required.

Energy intensity, conservation, efficiency

Gross Domestic Product

x unit of usefull result

- **Energy intensity** (EI)
  Amount of energy per unit of intended (i.e., useful) result.
  - EI of a country: energy consumption per GDP unit; (PIL)
  - EI of a product: (average) energy consumption per product unit; — average energy to obtain a product
  - EI of a service: (average) energy consumption per served request;
  - ...

  average to do a service

- **Energy conservation**
  Reducing the (growth of) energy consumption in absolute physical terms. consume less [J] per period or increase by less J

≠

- **Energy efficiency** (reduce consumption per unit) NOT the consumption itself
  Reducing the EI of a product/service/whatever while preserving the intended result (e.g., less energy for HVAC with the same comfort).

different optimiz.

$\Rightarrow$ Conservation and efficiency are separate but intertwined concepts, and automation (to say nothing of process/control co-design) is useful to pursue them.

different figure of merit

Some control problems – fundamental

– necessary to run energy syst

(like a Thermo generator that deliver II en from Fuel)

(foundam. problems)

"Generating" = TRANSFORM energy

TRANSITION PE → SE

- **Generator control** (PE→SE) from primary to deliver secondary energy
  - Minimise fuel consumption (NRES) – maximise caption (RES),
  - that is, stay in the vicinity of "optimal" operating points.

  → optimal work region

- **Utiliser control** (SE→final use)
  - Maintain functional quality (room temperatures, correct appliance operation,...).
- **Transmission control** (one type of SE) (secondary energy) → easy to transmit between parts
  - Maintain generation–demand balance;
  - Manage storages if applicable; maintain a certain quality requirem.
  - Maintain network operation quality (voltage and frequency, gas pressures,...); ↑ needed flow rate
  - Minimise network losses; → if some energy flow, must reduce the losses on net of trasmission
  - Avoid network overloading.

(don't exceed network capacity, NOT overload)

Some control problems – advanced problems

you have more en sources, you choose the best mix!

choose optimal mix

- **Generator energy mix control (NRES)**
  - Mix PEs (e.g., oil and gas)
  - to fulfil SE demands (e.g., electricity and steam)
  - optimising for cost, pollutant emission, or any combination thereof.
- **Utiliser energy mix control**
  - Mix available SEs (e.g., electricity, gas and solar heat stored as hot water)
  - to fulfil final use needs (e.g., electric and thermal loads of a house)
  - optimising for any Key Performance Indicator (KPI) related to the utiliser process.

    ↳ economic or others

    Index of quality
- **Zone- (or neighbourhood-)level energy mix control**

  OR "district" IS a certain perimeter where I have same rules

  - Given a zone with various generators (both RES and NRES) and utilisers,
  - find the optimal management of each generator and utiliser
  - and also of storages where applicable
  - optimising for...? Defining zone-level KPIs is an open problem and often involves conflicts among stakeholders' interests (e.g., we all cook dinner in the evening but gas suppliers prefer flat demand profiles).

↳ where all generators / utilisers are under a single autorities (like a CAMPUS)

Control problems – main common characteristics

shared

⇓ high level on how approach it

optimal control

- Set point tracking and/or functional minimisation;
- set point profiles generation; → define the optimal reference, how to generate set point
- scheduling (of generation, utilisation,...);
- disturbance rejection; → for tuning ecc.. some conflicts on requests
- uncertainty (e.g., demand forecast errors, time-varying costs,...);
- hard constraints (e.g., generator operational limits,...); that cannot be exceeded
- soft constraints (e.g., regulations/agreements on acceptable transient overloads, reserve management,...); Tollerable limit
- robustness versus plant–model mismatches (e.g., line impedance variations owing to weather conditions,...); large systems! can be under-actuated for maintenance
- fault tolerance (e.g., in the case of generator breakdowns).

{High level idea}

Recap

- Automation in energy system means controlling generation, transmission, storage and utilisation. . .
- . . . in a coordinated manner
- and for multiple objectives at different system levels.

- Control problems call for a coordinated use of various techniques
- and solutions need implementing in heterogeneous architectures.
  (various syst connected)
- Process/control co-design is helpful wherever applicable
- but refurbishing of already designed systems is of paramount relevance.

Needs

establish
(theoretical optimum)

⇑

indicators to check goodness
for control

∀ subj a model is needed

- A modelling framework;
- quantitative performance indicators (automation-oriented KPIs);
- a problem taxonomy; → system view, dynamic behav classification
- best practices and control design guidelines based on the above,
- and corresponding validation/assessment methodologies;
- awareness of implementation-related facts.

Next steps

clarify the difference!

- Review modelling principles;
- define a modelling framework suitably managing components' behaviours and interfaces in both the object-oriented (OO) and the block-oriented (BO) context, conceptually relating the two;
- devise the required component models (of course we shall not exhaust this matter) and the major KPIs;
- learn to create system-level compound models tailored to handling problems that involve those KPIs.