Modeling and integration of renewable energy

Application to datacenters

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Introduction

Fossil fuels are slowly being replaced by cleaner sources

Sinking renewable energy sources (RES) costs enable their development:

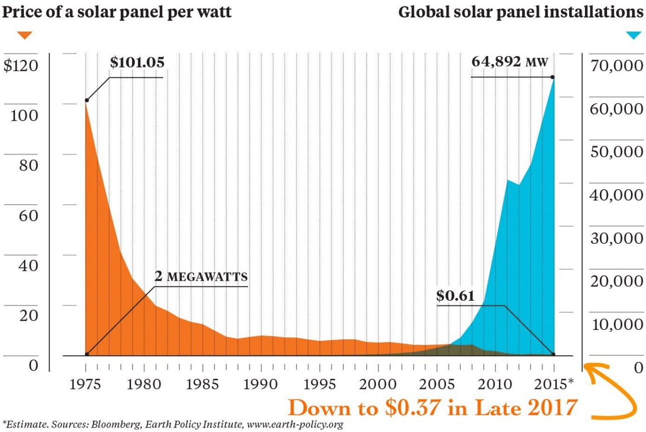

Figure 1: PV installed capacity vs. price [Source: cleantechnica.com]

RES supply options

Three options for integrating RES with a datacenter:

- Buying RES power from a utility: simple, economically but not physically clean!
- Local grid-connected RES supply: rather simple but requires space
- Local islanded system RES supply: expensive, complex design and control

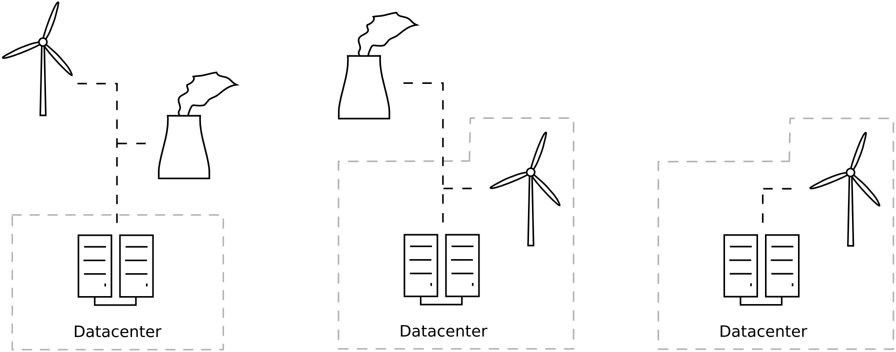

Figure 2: Comparison of the three options

So why is it not so simple?

Three main reasons come to mind:

- Generation **must** match demand in **real time**, or vice versa
- RES output of intermittent, variable, **non-dispatchable**, and hard to predict
- Energy is bought/sold on **hourly** markets

This means that meeting datacenter objectives is more difficult than with conventional, controllable sources:

1. Maximum reliability / quality of service
2. Minimum costs

Goals of this presentation:

- Introduce RES and storage unit types and models
- Discuss the challenges associated to their integration in datacenters
- Facilitate work on these topics for IT researchers

Renewable sources (1)

Main types of renewable energy sources:

- Photovoltaic panels
- Wind turbines
- Hydro power plants
- Biomass

The choice of a source depends on:

- Available resources: solar radiation, wind speed, etc.
- Available area
- Capital, operation and maintenance costs
- Availability and cost of grid power
- Incentives, legislation, permitting, etc.

Example for PV:

- About 150-200 W/m^2 of power output, in the best case
- About 1450 kWh/m^2 received solar radiation per year in Toulouse

Renewable sources (2)

For example, using wind turbines in windy Northern Norway makes both economic and technical sense[1], while using PV panels does not

Figure 3: Wind turbines in the Raggovidda wind farm in Norway [Source: haeolus.eu]

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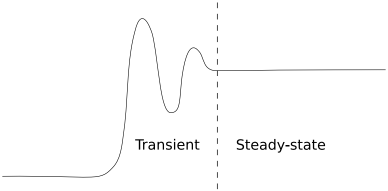
[1] Despite power export issues

Categories of models

So how do I model this type of device?

Different categories of models may be used:

- Static/steady-state vs. transient
  - Static: approximated, no dynamic behavior (e.g., for a wind turbine)
  - Transient: detailed, contain differential equations
- Voltage-current vs. power
  - Votage-current: voltage and radiation as input, current as output (example)
  - Power: radiation as input, power as output



If your focus is on slow dynamics (> minute), a power-based, static model will do!

Model example: PV (1)

A basic, generic model is as follows:

$$P_{pv}(t) = N_{pa}\,\eta_{pa}\,S_{pa}\left(I_{sun}(t)\cdot\frac{\sin(\alpha+\beta)}{\sin(\alpha)}\right)$$

$$0 \leq P_{pv}(t) \leq N_{pv}\,P_{pa,max}$$

- N_{pa}: number of panels
- η_{pa}: panel efficiency ($\approx$ 0.15-0.25)
- S_{pa}: panel area
- I_{sun}: horizontal solar radiation
- α and β: solar and tilt angle

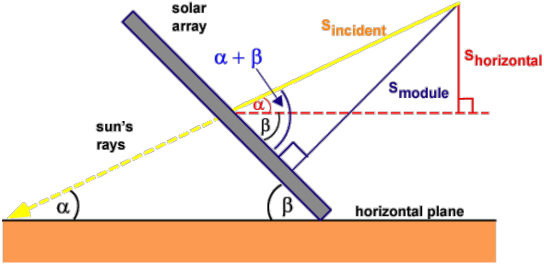


Figure 4: Illustration of the tilt angle ($S_{horizontal} = I_{sun}$) [Source: pveducation.org]

Model example: PV (2)

Also for a PV plant, a more detailed model considers:

- Voltage/current (but not dynamics: there is no moving part)
- Panel characteristics, available on datasheets
- Panel temperature

$$I_{rs}(t) = \frac{I_{sc}}{\exp\left(\frac{q\,V_{pv,oc}}{N_s\,k\,A\,T_c(t)}\right) - 1}$$

$$I_s(t) = I_{rs}(t)\left(\frac{T_c(t)}{T_{ref}}\right)^3 \exp\left(\frac{q\,E_g}{k\,A}\left(\frac{1}{T_{ref}} - \frac{1}{T_c(t)}\right)\right)$$

$$I_{ph}(t) = (I_{sc} + K_i\,(T_c(t) - T_{ref}))\,I_{sun}(t)\,\frac{\sin(\alpha+\beta)}{\sin(\alpha)}$$

$$I_{pv}(t) = \alpha_{pv}(t)\,N_p\,I_{ph}(t) - N_p\,I_s(t)\left(\exp\left(\frac{q\,V_{pv}(t)}{N_s\,A\,k\,T_c(t))}\right) - 1\right)$$

$$P_{pv}(t) = V_{pv}(t)\,I_{pv}(t)$$

Model example: PV (3)

Note that virtually any power (or voltage/current) can be reached using series and parallel combinations of basic elements, here solar cells:

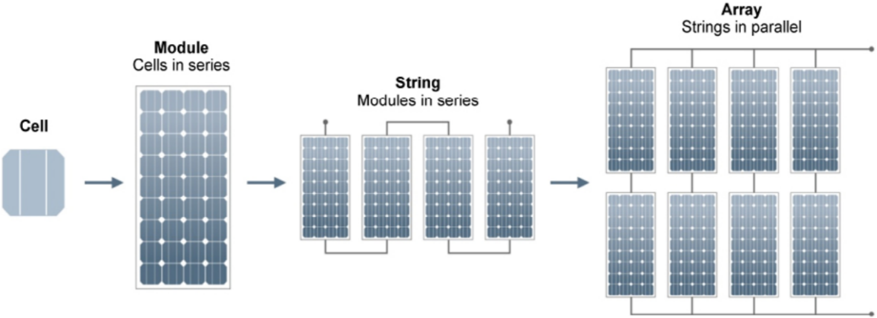


Figure 5: Datacenter load and solar radiation profiles over 5 days [Source: yourhome.gov.au]

The same principle holds for electrochemical storage units (batteries, fuel cells, etc.)

Model example: PV (4)

The panels must also be connected to the grid (utility or local) through power electronics devices, such as inverters or DC/AC converters:

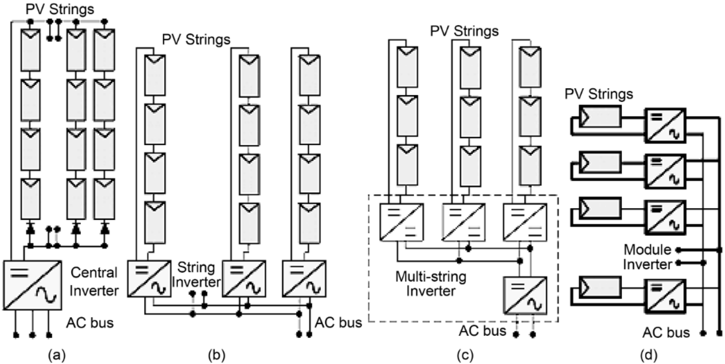


Figure 6: PV string connection possibilities through inverters [Source: 10.4236/cs.2016.713339]

These inverters also decrease the efficiency (> 90%), as do cable losses. . .

The need for energy storage

However, as renewables are non-dispatchable, it cannot adequately supply the load: energy storage must be added

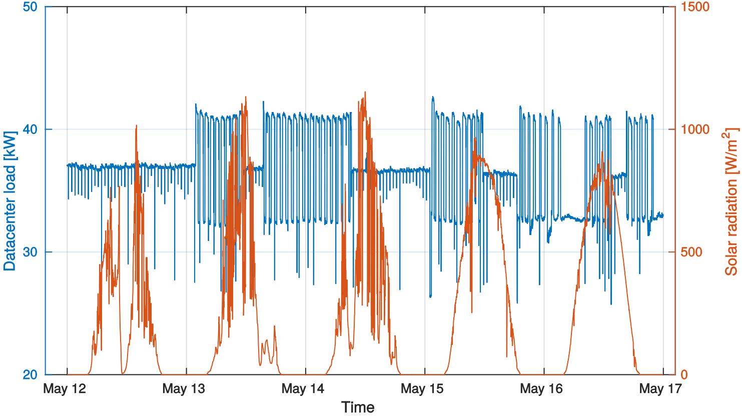


Figure 7: Datacenter load and solar radiation profiles over 5 days

Energy storage technologies (1)

But many types of storage technologies exist!

Examples of technologies:

- Batteries: lead-acid, lithium-ion, NaS, etc.
- Hydrogen-energy
- Supercapacitors
- Others: pumped hydro, flywheel, SMES, CAES, etc.

The choice of a technology depends on:

- Availability of resources (CAES, pumped hydro)
- Required power (W) and energy (Wh, or discharge time), the main technical criterion
- Required response time (W/s)
- Capital, operation and maintenance costs
- Round-trip efficiency(?)

Energy storage technologies (2)

Figures like this are commonly used to summarize typical use ranges, but these ranges primarily result from economic constraints:

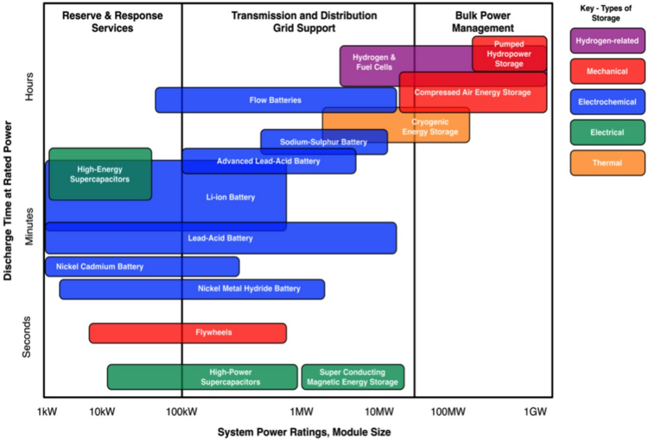


Figure 8: Typical power and energy ranges of some storage technologies [Source: energystoragesense.com]

Hybrid energy storage (1)

A typical choice with PV would be batteries, with obvious economic limitations:

- Either use an extremely large and expensive battery
- . . . or have way too much generation in summer, leading to curtailments
- . . . and not enough in winter, leading to load shedding

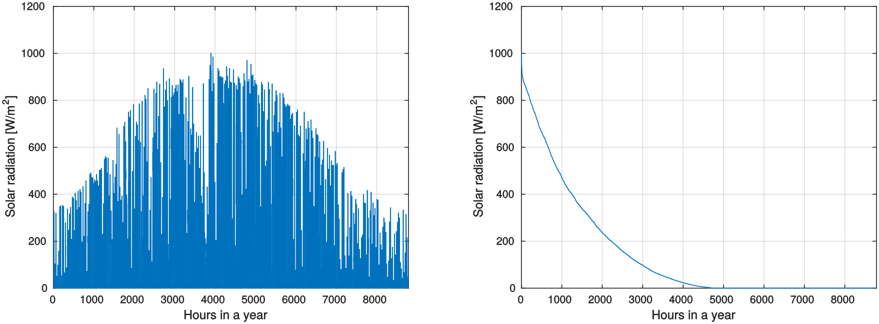


Figure 9: Solar radiation data and duration curve over a year in Genève

Hybrid energy storage (2)

As a consequence, in some cases, hybrid storage can make sense:

- Use batteries for short, day/night cycles
- Use hydrogen-energy storage for long, seasonal patterns

Structure and operation of a hydrogen-energy storage system:

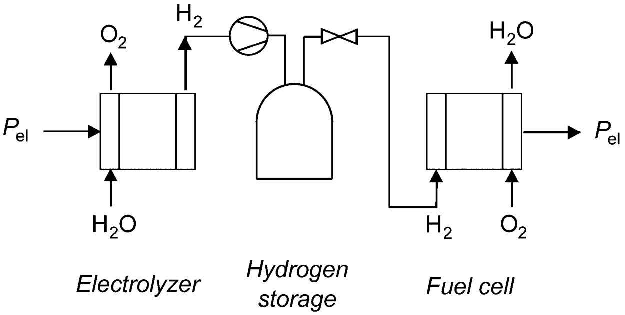


Figure 10: Principle of hydrogen-based energy storage [Source: 10.1039/C4EE04041D]

Model example: lithium-ion battery (1)

A generic energy storage model is as follows:

$$SOC(t+\Delta t) = SOC(t) + \frac{P_{bat,ch}(t)\,\eta_{bat,ch} - P_{bat,disch}(t)/\eta_{bat,disch}}{E_{bat}}\,\Delta t$$

$$SOC_{min} \leq SOC(t+\Delta t) \leq SOC_{max}$$

$$SOC(0) = SOC_{init}$$

$$0 \leq P_{bat,ch}(t) \leq P_{bat,ch,max}$$

$$P_{bat,disch,max}(t) \leq P_{bat,disch}(t) \leq 0$$

where SOC stands for state-of-charge and E_{bat} is the battery capacity

As for PV, batteries are scalable to the multiple MW/MWh size, and static DC/DC or DC/AC power converters must be used

Model example: lithium-ion battery (2)

A more detailed, voltage/current model considers the open-circuit voltage and internal impedance of a battery cell:

$$E(t) = E_0 - K \frac{n_{bat,p} C_{\max}}{n_{bat,p} C_{\max} - DOD(t)} + A\, e^{-B \cdot DOD(t)}$$

$$V_{bat}(t) = E(t) - R_{bat}\, I_{bat}(t)$$

$$SOC(t) = SOC(t-1) + \eta_{bat,ch/disch} \frac{I_{bat}(t)\,\Delta t}{C_{bat}}$$

$$DOD(t) = 1 - SOC(t)$$

$$SOC_{min} \leq SOC(t + \Delta t) \leq SOC_{max}$$

$$SOC(0) = SOC_{init}$$

$$I_{bat,disch,max} \leq I_{bat}(t) \leq I_{bat,ch,max}$$

Note that much more detailed models exist: electrochemical devices are complex

Integrated system

Putting RES and the multiple storage units together, a datacenter supply system can be designed around a DC or an AC bus (which impacts converters, losses and costs)

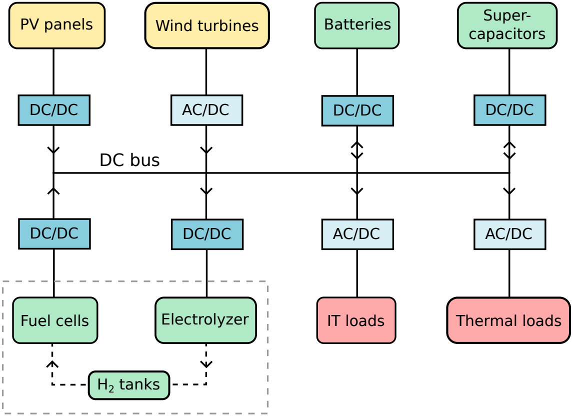


Figure 11: Architecture of a DC datacenter supply system integrating RES and storage units, used in the DATAZERO project

Energy management (1)

Energy management and control themselves are challenges:

- Both generation and load are uncertain: forecasting is required
- Rolling-horizon, day-ahead scheduling is often used
- . . . and corrected in real-time to account for forecasting errors

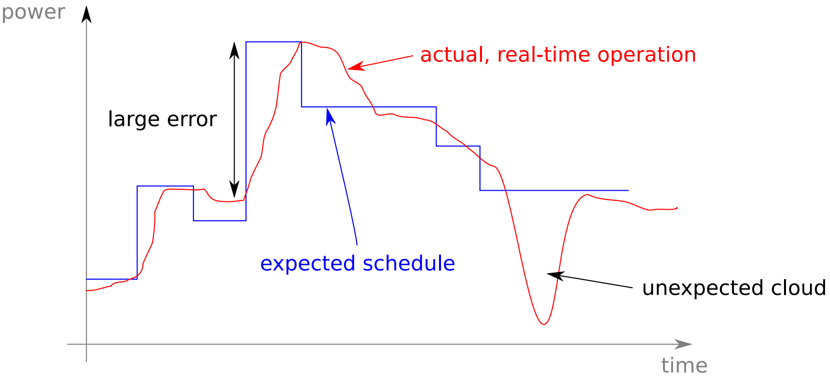


Figure 12: Day-ahead scheduling and real-time control principles

Energy management (2)

Several algorithms are thus combined, and must consider faults, grid conditions (prices, congestion, etc.), security constraints, demand response, etc.

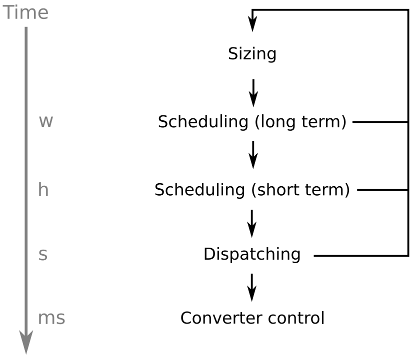


Figure 13: Energy manamagent system layers example

But what is the objective function, if there is no operation cost?

Component aging (1)

Considering component aging and degradation may be an idea

For example, for a fuel cell (similar to a battery, without capacity fade):

- The impedance increases, leading to a voltage and efficiency drop
- The maximum current/power also decreases, which the control strategy should consider!

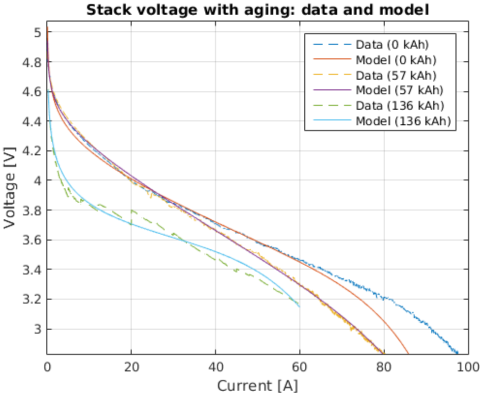


Figure 14: Polarization curve of a fuel cell stack over time and use

Component aging (2)

Aging models are thus used together with diagnostics and prognostics algorithms to manage performance degradation and facilitate maintenance

Difficulties lie in the complex causes of aging (high currents, calendar, cycling, temperature, fluids management, etc.), hence the growing use of machine learning

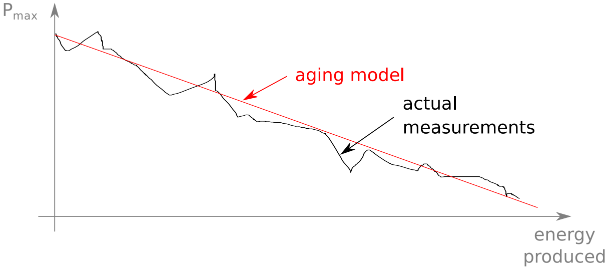


Figure 15: Conceptual example of prognostics application of an aging model

Regarding the cost function, the average capital cost per produced MWh can be used to consider replacement costs

Other challenges

Additional issue examples include:

- Sizing: how to maximize QoS and efficiency and minimize costs?
- Reliability: what does 2N or 2N+1 mean for a hybrid system?
- Ancillary services: how can a datacenter support the grid and generate profit?
- Coupling with heat management?

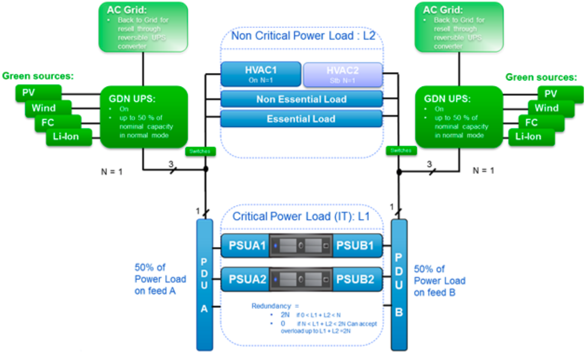


Figure 16: A proposed 2N architecture for datacenter supply within the DATAZERO project

Conclusion (1)

On RES and storage unit models:

- Plenty of models exist: use the most adequate ones for your application
- Do not reinvent the wheel!

Useful online resources:

- Matlab models are available upon request (soon on Github)
- Weather and other related data: see robinroche.com
- Cost data: see lazard.com/perspective or in DOE/EIA publications

On integration challenges:

- Intermittent RES are profoundly changing energy supply systems
- This also holds for IT systems, for which the consumption keeps growing
- Using flexibility on the IT and power sides seems to be a promising area of research

Conclusion (2)

Parts of this work were conducted within the DATAZERO project:

- Funded by the French ANR (2015-2019)
- Models and explanations may be found in delivrable D2.4
- **A dedicated workshop will be organized in Belfort at the end of 2019!**
- Website: datazero.org

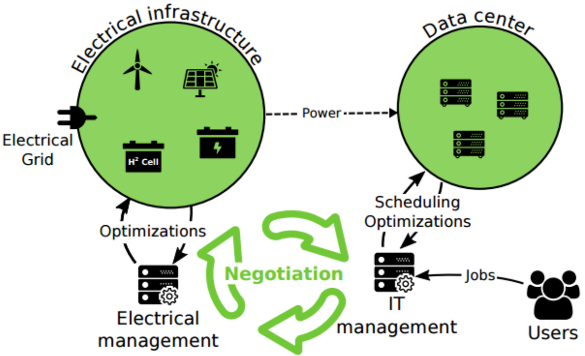


Figure 17: Overview of the DATAZERO project concept

Thank you for your attention

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