Renewable energy balance and techno-economic analysis

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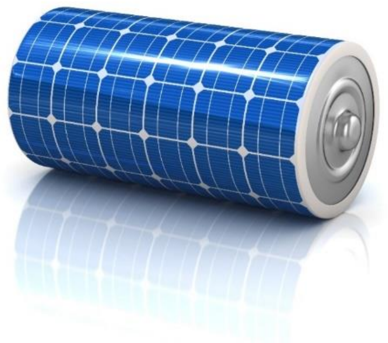
Methods for analyzing energy efficiency and renewable energy technologies

Objectives

1. Understand principles of techno-economic analysis of energy system
2. Understand basics of energy balance calculations
3. Introduction to concept of Prosumers
4. Understand method to perform techno-economic assessment of an energy technology using example of home PV and battery system

Content

1. Techno-economic analysis of energy technologies
2. Renewable energy balance
3. Prosumers
4. PV techno-economic analysis
5. Battery techno-economic analysis



Techno-economic analysis of energy technologies

Purpose of techno-economic analysis

- Typically, there exist several technologies for a given application (e.g. supplying electricity to a house)

Which of these alternatives is best from a techno-economic (technical and economic/financial) point of view?

- Cost
- Energy savings
- Emissions
- Other criteria, constraints: space, maintenance, etc.

Steps

1. Determine the aim of the analysis
   – Why, for whom, targets, time frame and level of accuracy
2. Determine the needed functionality, technology requirements
3. Set system boundaries (like LCA)
   – Single process versus the complete supply chain of processes
4. Analyse existing or reference processes as a base for comparison
5. Identify the whole technological space, i.e. all possible technologies, future cases
6. Identify relevant constraints
   – e.g. physical and consumer preferences, which may limit the technological space

Reference: Kornelis Blok and Evert Nieuwlaar, Introduction to Energy Analysis, 2nd Edition (2016)

Economic indicators

- New energy technologies are **investments**
- Investments made by both private and public entities
  - Expect a **return on investment**
- When considering options that don’t exist, also want to compare which will be most cost effective
- Under ‘free market’ assumptions, most cost effective solutions should ‘win’
  - **Evidence suggests that this is <u>not</u> the case in reality**

Present value of money

- Money today is worth more to you than money in the future
- Simple example: you prefer to get 1000CHF now than 1000CHF in 20 years time.
- Why?
  - You need/want money now (time value of money)
  - You don't trust that in 20 years I will make sure you get your cash (risk)
  - You think in 20 years 1000CHF will be worth less (inflation)
  - You don't care what happens in 20 years time (investment time horizon)
- Similar consideration if I ask you to invest 1000CHF today in return for future payback

Present value and the discount rate

Present value$= \frac{\boldsymbol{Future\ value}}{\boldsymbol{(1+r)^n}}$

- r: **discount rate** (%)
- n: number of periods until the future value is received (typically years)
- **Economic discounting should be done per year.**

Discount rate

- The discount rate is the rate used to calculate the present value of cash flows.
- Should be based on:
  - Risk
  - Inflation
  - Time value of money
  - Your time horizon as a stakeholder…

Discount rates depend on stakeholder perspective

- How much you discount the future depends on your point of view and goals!

The private perspective
(10% or higher)

e.g. private investors

The social perspective
(2-6%)

e.g. government

Financial indicators

- When we invest in new technologies we use several key indicators to compare different options:
  - **CAPEX (CHF)**
  - **OPEX (CHF)**
  - **Pay back period (years)**
  - **Net Present Value NPV (CHF)**
  - **Levelised cost of energy (CHF/kWh)**
  - **Levelised value (CHF/kWh)**
  - **IRR (%)**

CAPEX: CAPital Expenditure (CHF)

- Investment in ‘capital’
  - Usually refers to fixed assets like machines (e.g. wind turbine), power transmission systems, etc.
  - Things that you buy once and keep for a certain lifetime
- Can be both at the start of a project and throughout its lifetime
  - E.g. replacing parts of a system such as a battery within a PV + Battery system

OPEX: OPerating Expenditure (CHF)

- Ongoing costs for systems e.g. Maintenance
- For fossil fuel plants, includes fuel costs (coal, gas)
  – One of the biggest advantages of renewable electricity is **zero** ongoing fuel costs
  – Today, it's cheaper in parts of the world to build wind and solar than to pay fossil fuel plant OPEX

Pay back period (years)

$$PBP = \frac{Initial\ Investment}{Annual\ Net\ Cash\ Flow}$$

- How many years to get back the cash I put in?
- Does **not** account for the time value of money (discounting)

Net Present Value (CHF)

$$\boldsymbol{NPV = \sum_{t=0}^{n} \frac{CF_n}{(1+r)^n}}$$

In each year we have benefits, capital and operating expenditure:

$$\boldsymbol{CF_n = Benefit_n - CAPEX_n - OPEX_n}$$

- Compares the financial benefit taking into account the costs each year and the discount rate (time value of money)

Levelised Cost of Energy LCOE (CHF/kWh)

- Calculate overall cost of energy accounting for discounting
- Multiple ways to calculate LCOE with different assumptions
- The following formula calculates using the **discounted revenue** required to match the **discounted costs**

$$\boldsymbol{LCOE = \frac{CAPEX + \sum_{n=1}^{Lifetime} \frac{OPEX_n}{(1+r)^n}}{\sum_{n=1}^{Lifetime} \frac{E_{Generated,n}}{(1+r)^n}}}$$

- *r* (%) : discount rate
- *Lifetime* (years) : how long the system element lasts
- $E_{Generated,n}$ (kWh): annual generation
- *n :* year

Why is LCOE important?

- Useful way to evaluate **and compare** energy technology options
- To be competitive, should be *at least* within an ‘acceptable’ range of costs that users are willing to pay
  - Doesn’t have to be the cheapest option if there are other advantages, constraints, motivations
    - e.g. energy security, incumbency

Levelized cost example

- Determine the levelised cost of a boulangerie’s oven with the following details:
  - Capital expenditure (CAPEX): 10000 CHF
  - Operation expenditure (OPEX): 300 CHF/year
  - Number of croissants made per year: 7000
  - Lifetime of oven: 3 years
  - Discount factor: 2%

Levelized cost example

🥐 = Croissant

$$LC_{oven} = \frac{10000\ CHF + \frac{300\ CHF}{(1+0.02)^1} + \frac{300\ CHF}{(1+0.02)^2} + \frac{300\ CHF}{(1+0.02)^3}}{\frac{7000\ \text{🥐}}{(1+0.02)^1} + \frac{7000\ \text{🥐}}{(1+0.02)^2} + \frac{7000\ \text{🥐}}{(1+0.02)^3}}$$

$$LC_{oven} = 0.54\ \frac{CHF}{\text{🥐}}$$

← Total selling price of croissant must include these costs (plus other costs of bakery)

Levelised Value

- Gives the revenue per unit energy
- Unlike LCOE, depends on how much you can sell energy for (difference between cost and revenue)

$$\boldsymbol{LVOE = \frac{\sum_{n=1}^{Lifetime} \frac{Revenue}{(1+r)^n}}{\sum_{n=1}^{Lifetime} \frac{E}{(1+r)^n}}}$$

- *Revenue* (CHF): Revenue of the system (e.g. from selling energy)
- *E* (kWh): total generation

Internal Rate of Return (%)

- **IRR** (%): Solve the NPV equation such that NPV equals zero

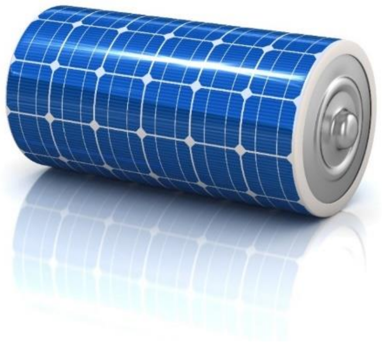
$$\mathbf{0 = \sum_{t=0}^{n} \frac{CF_n}{(1 + IRR)^n}}$$

- IRR 'replaces' the discount rate
  - Calculate the value instead of setting it, to produce a % return value
- Compares the value of the investment to the discounted value of your cash
- Useful for comparing profitability between different investments

Taxes and Subsidies

- The base equations presented **ignore** taxes and subsidies
- These are two important levers of (energy) policy
  - CO2 taxes (now unpopular)
  - Subsidies (RepowerEU, Inflation Reduction Act)
- Can substantially change balance in favour of different technologies, depending on structure/allocation

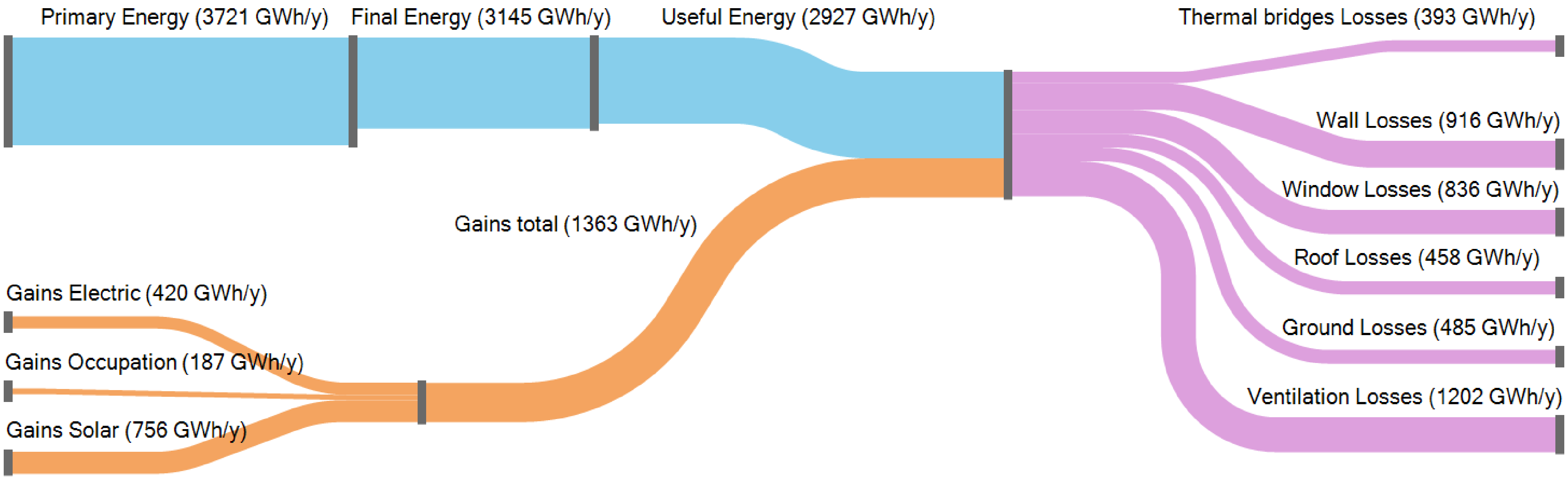
Renewable Energy balance



Energy balances

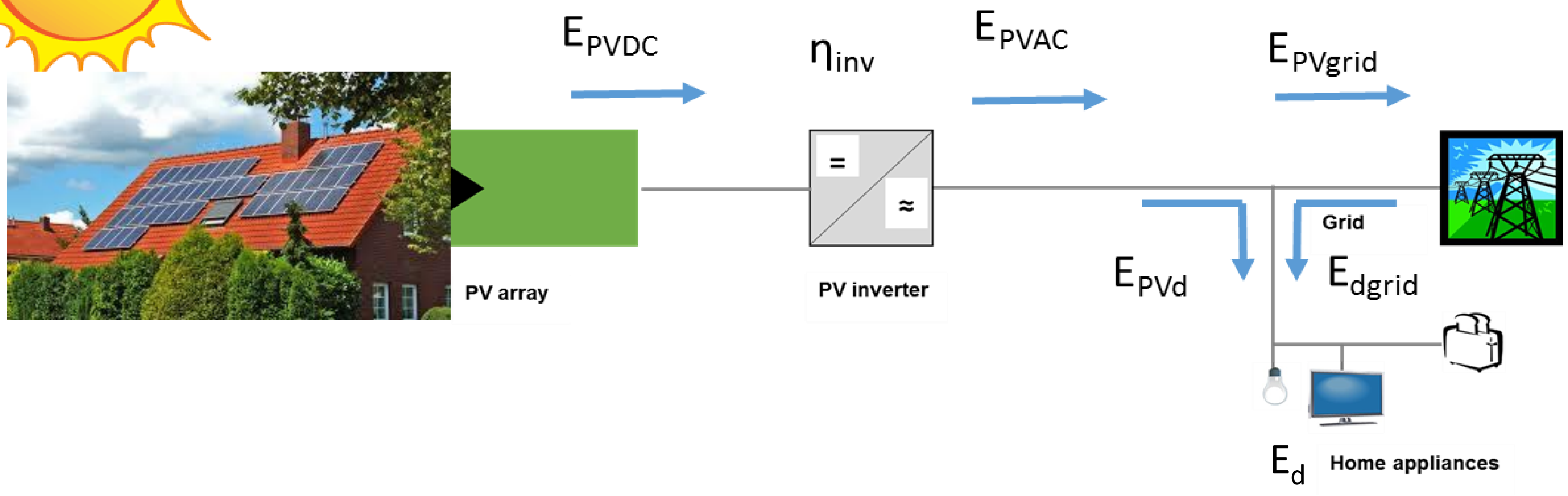
- The Law of Conservation of Energy
  - – Sum of energy in must sum equal energy out!
- First step to study an energy system
- Should include energy
  - Demand
  - Generation
  - Storage
- Consider temporal resolution (**when** we use energy)
  - – Matching power as well as energy

Heat gains and losses in office buildings

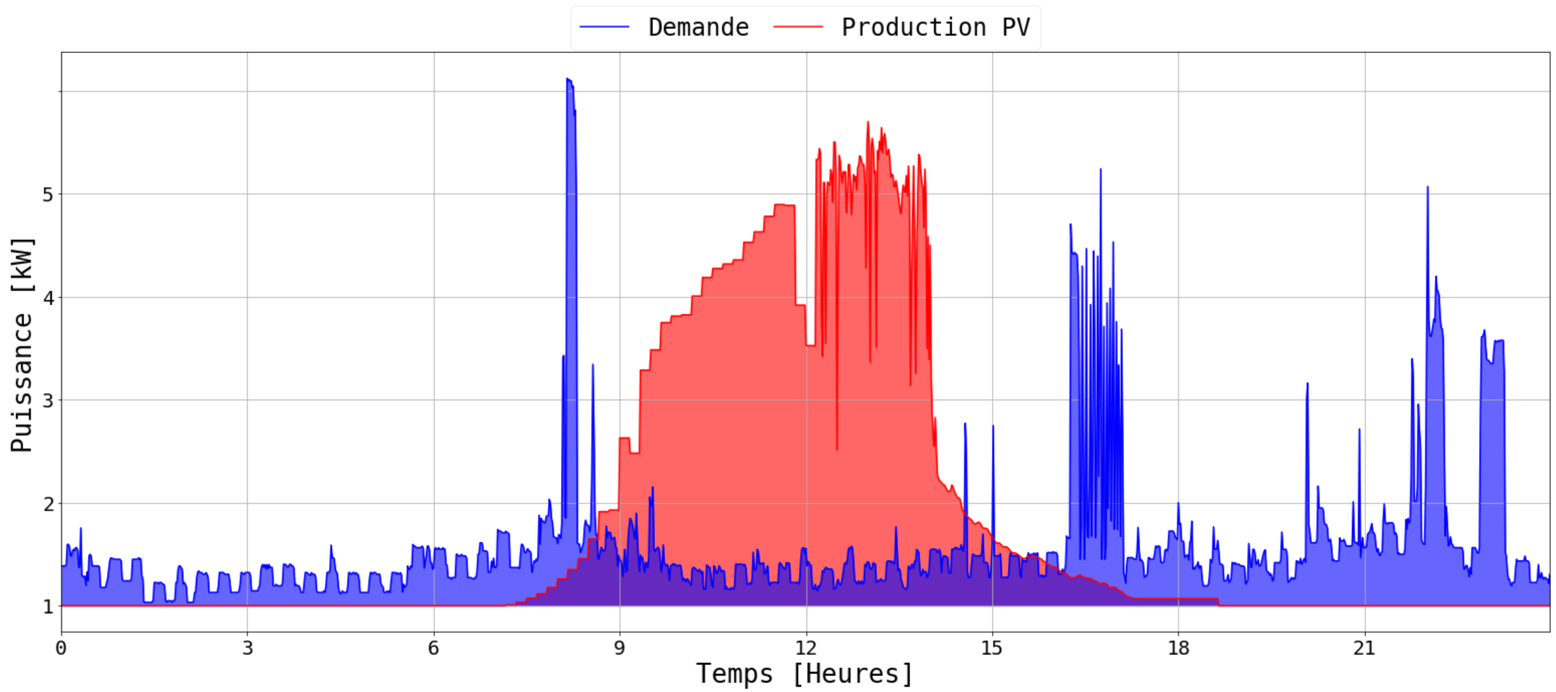


F. Sasso, J.Chambers, M.Patel; "Space heating demand in the office building stock: Element-based bottom-up archetype model"; *submitted Energy and Buildings*

PV Energy supply for one House



PV production and energy demand vary during the day



Pena-Bello et al. (2019), Renewable and Sustainable Energy Reviews

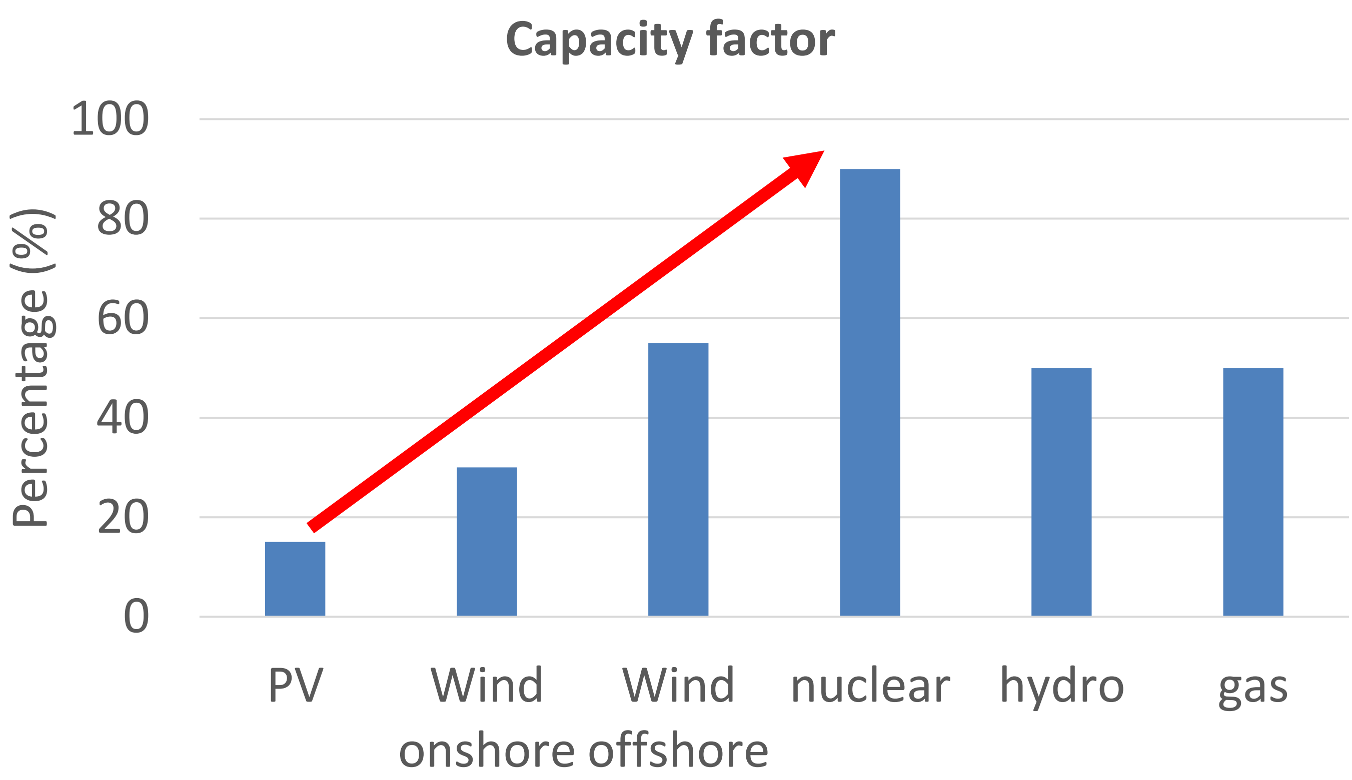
Capacity factor

Capacity factor (%)

$$C_{factor} = \left(\frac{Electricity\ generated\ (kWh\ per\ year)}{Nominal\ capacity\ (kW) \times 8760\ \mathrm{h}}\right) \times 100$$

- Overall indicator of how much of the maximum power generation capacity of a resource is available in practice
- Renewables (sun, wind): affected by variability of weather
- Nuclear, fossil: affected by maintenance, refuelling, cleaning

Capacity factor

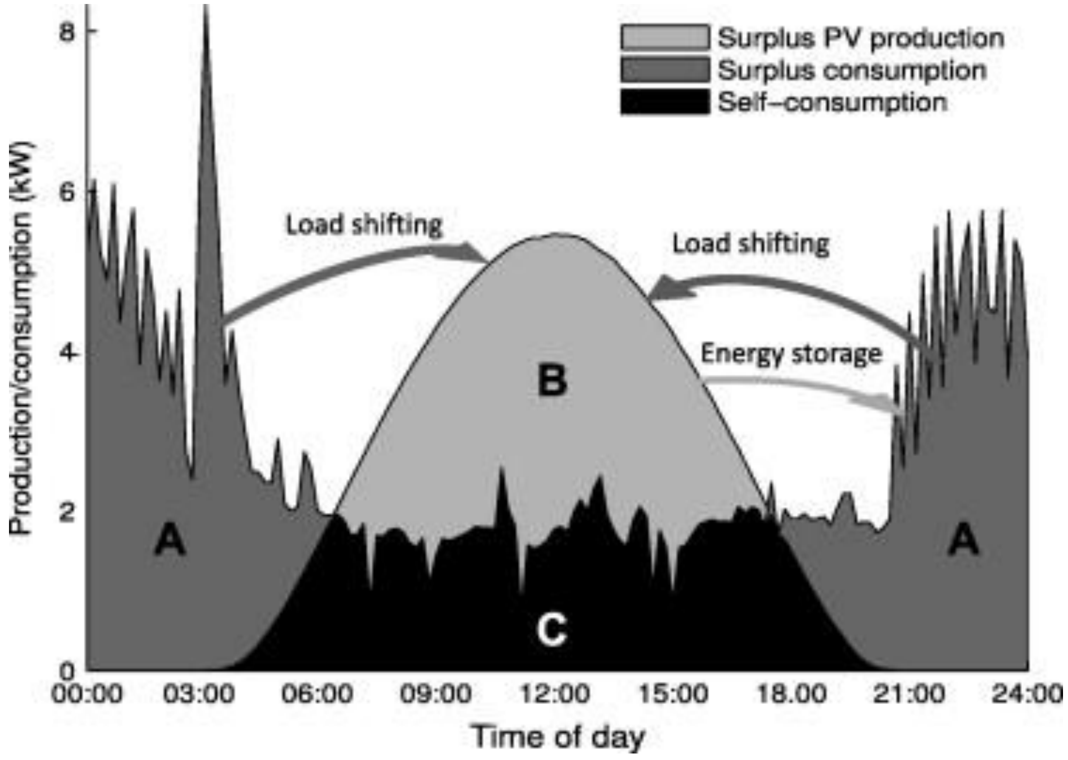


Source: International Energy Agency https://www.iea.org/reports/offshore-wind-outlook-2019

Capacity factor doesn't tell the whole story

- Generally calculated on a yearly basis
- For electricity, supply and demand must balance at ALL TIMES
- Capacity factor only tells you about the average over a year
- Matching supply and demand motivates need for:
  - Energy Storage (batteries, pumped hydro, thermal storage)
  - Load shifting

Self sufficiency and Self consumption



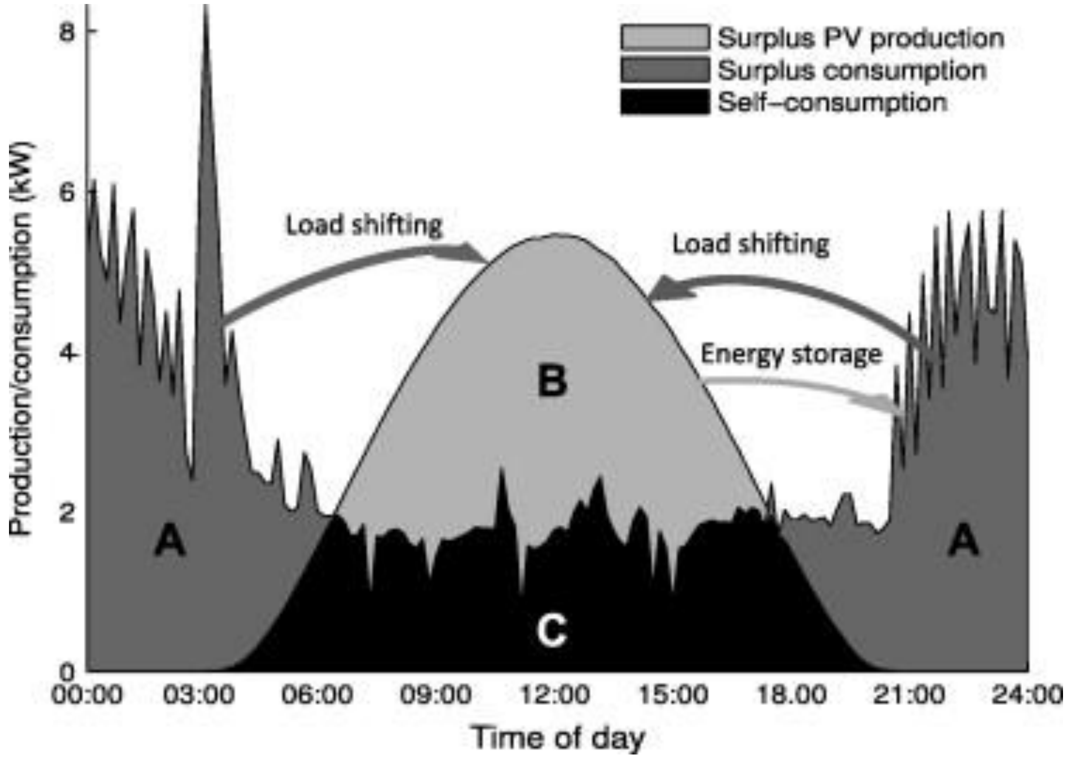
Luthander et al. (2015), Applied Energy

- Daily net load (A + C)
- Net generation (B + C)
- Absolute self-consumption (C) in a building with on-site PV.

$$Self\ consumption = \frac{C}{B + C}$$

$$Self\ sufficiency = \frac{C}{A + C}$$

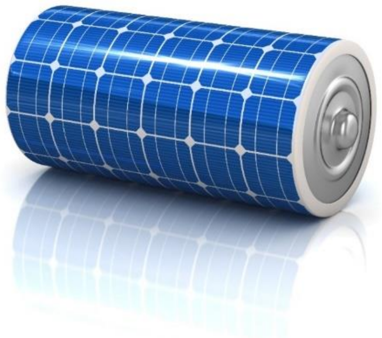
Load shifting and energy storage



Luthander et al. (2015), Applied Energy

- Load shifting: Changing the time when energy is used
- Energy storage: Storing energy when there is excess to use it later

Prosumers



Prosumers

A prosumer is a consumer who becomes active by generating their own energy

What are the motivations for individuals to invest in a PV (plus battery) system?

- Individual
  - Autarky
  - Financial
  - Social status
  - Perceived overall cost

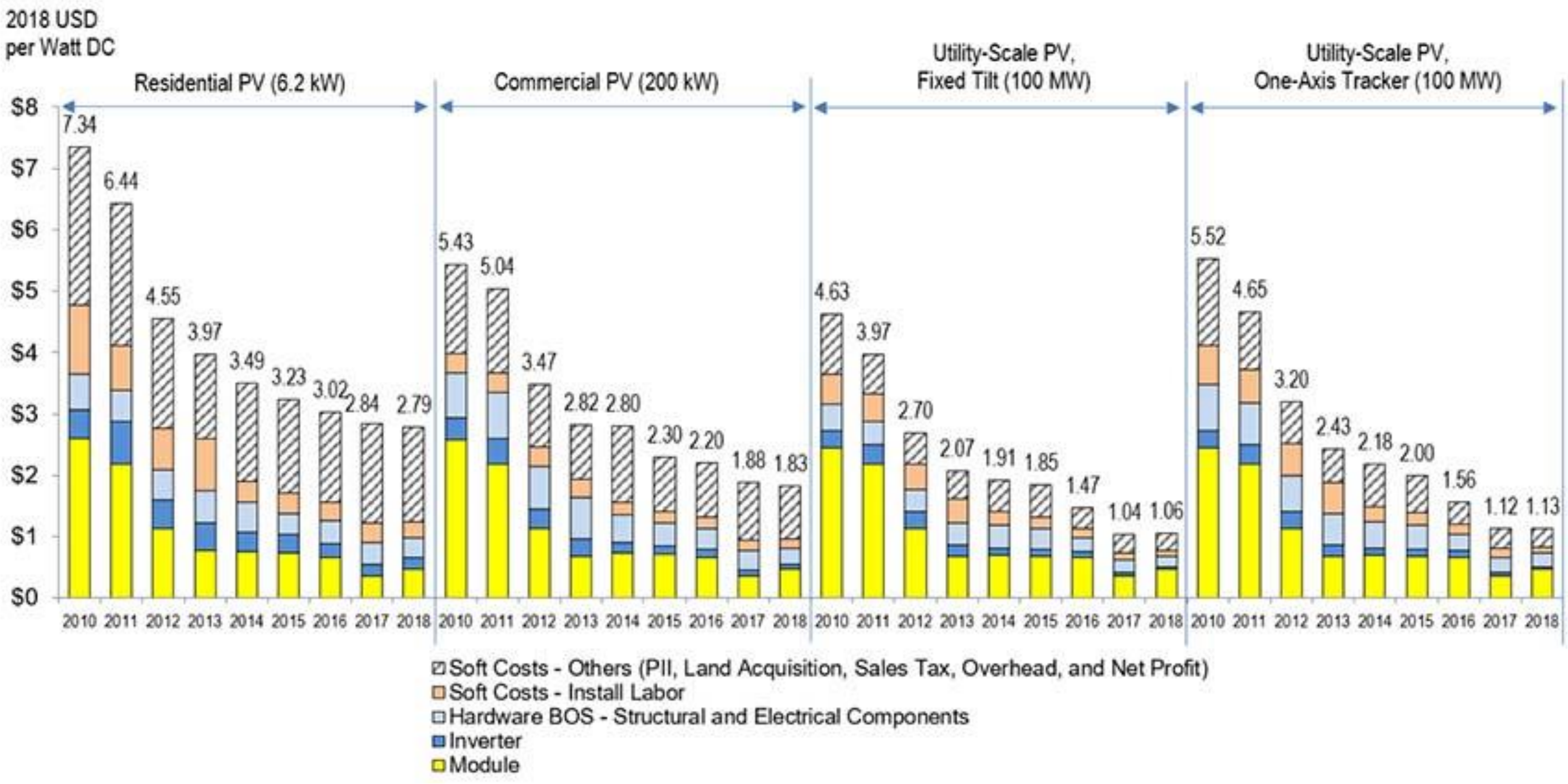
- Collective (social norms)
  - Economic
  - Environmental

- Policy
  - Laws and obligations

Economic motivations

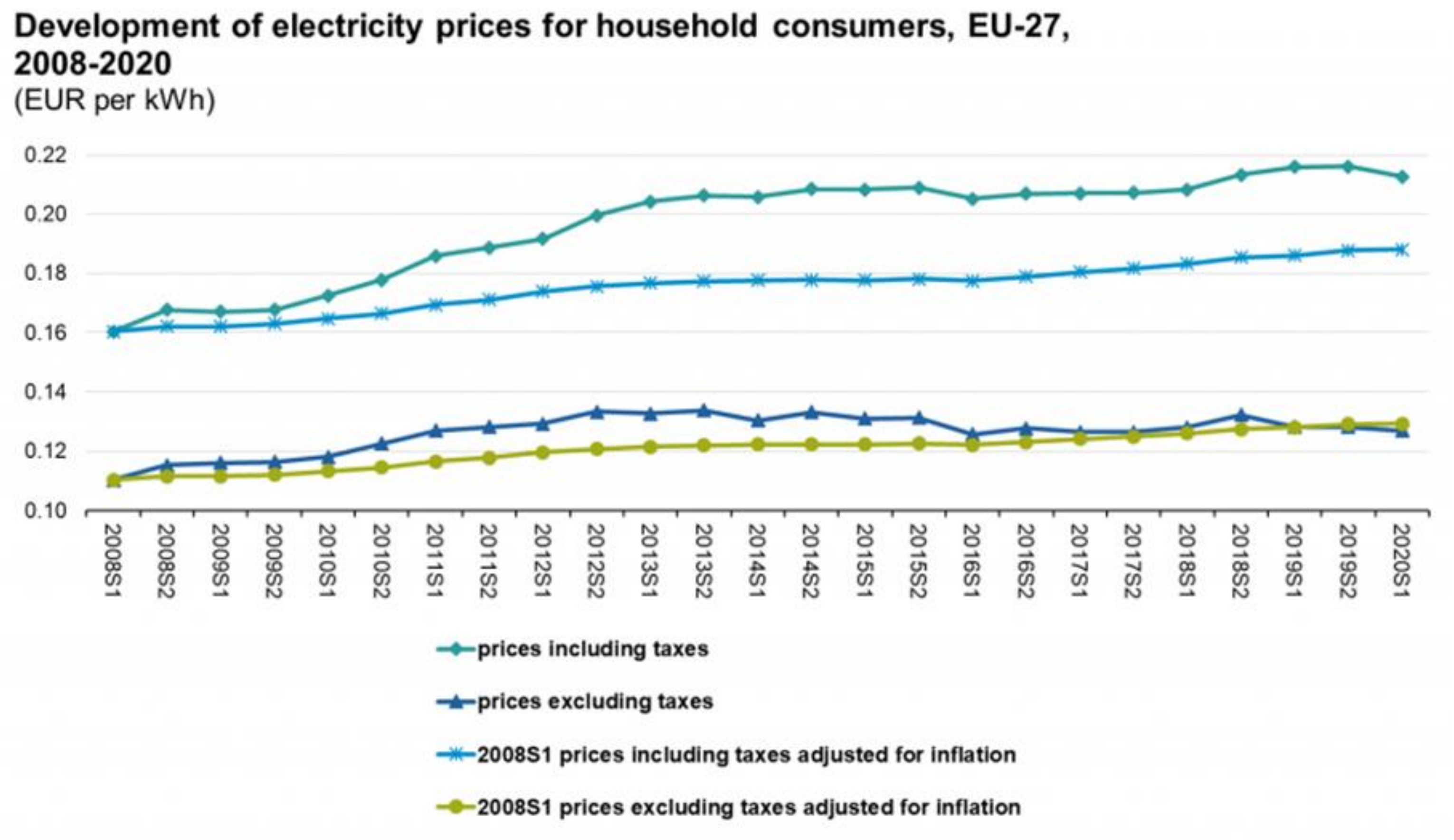
- *Ignoring* other aspects, consider attractiveness of PV and battery storage from financial perspective…

PV costs are dropping



NREL PV system cost benchmark summary (U.S. Solar Photovoltaic System Cost Benchmark: Q1 2018)

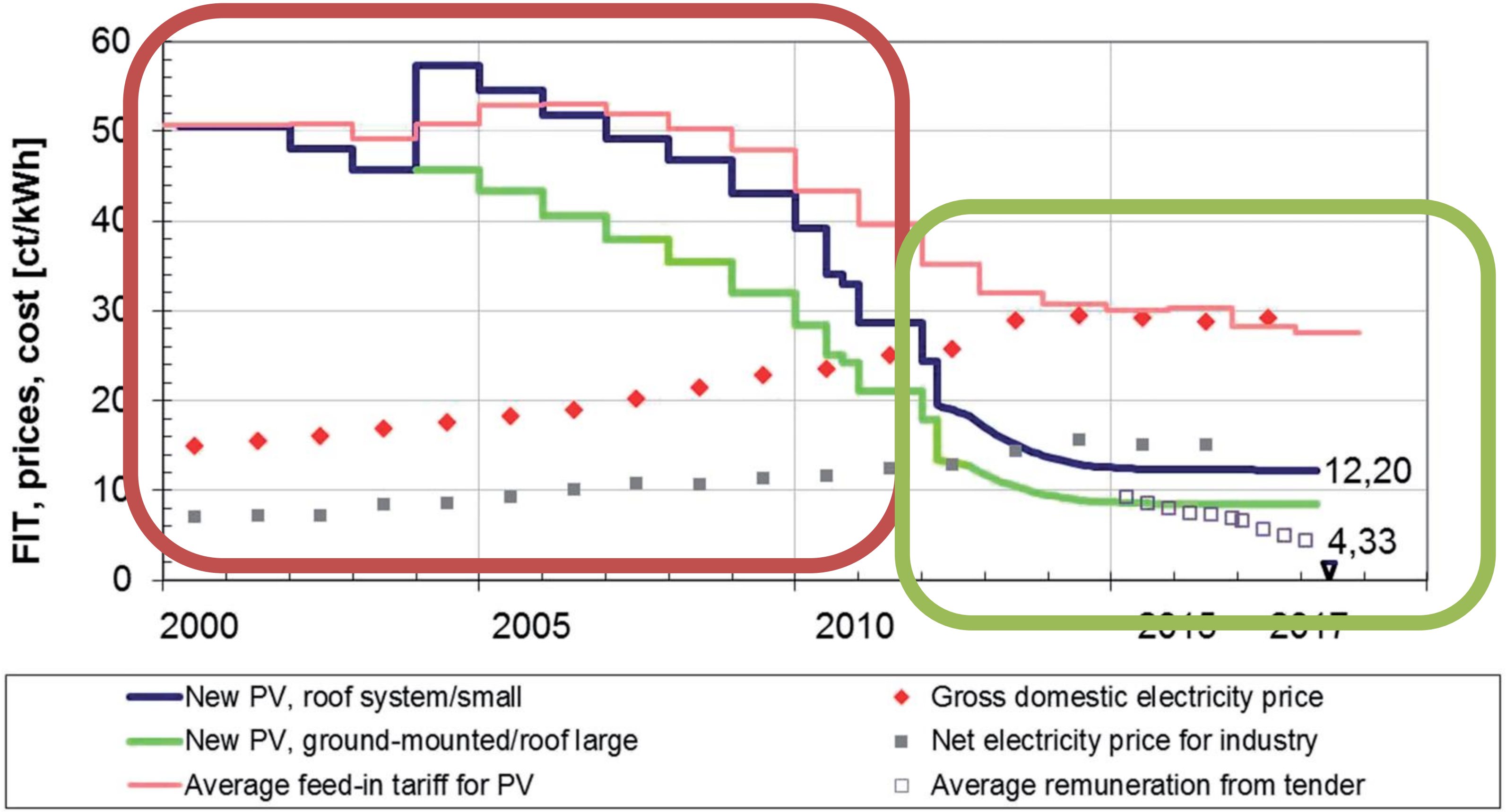
Electricity prices tend to increase



Development of electricity prices for household consumers, EU-27, 2008-2020 (EUR/kWh)

https://ec.europa.eu/eurostat/statistics-explained/index.php/Electricity_price_statistics

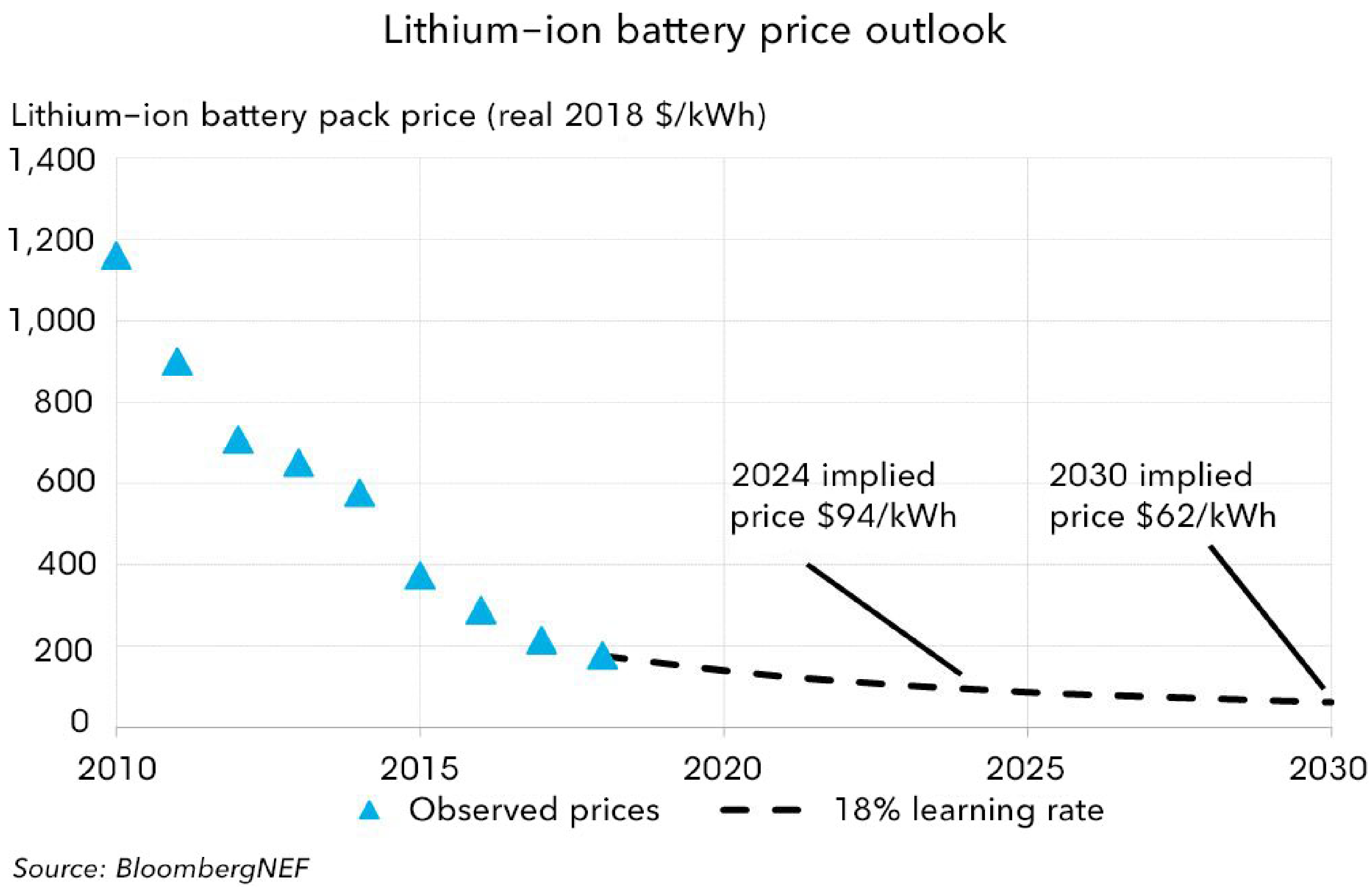
PV cost approaches price of grid electricity



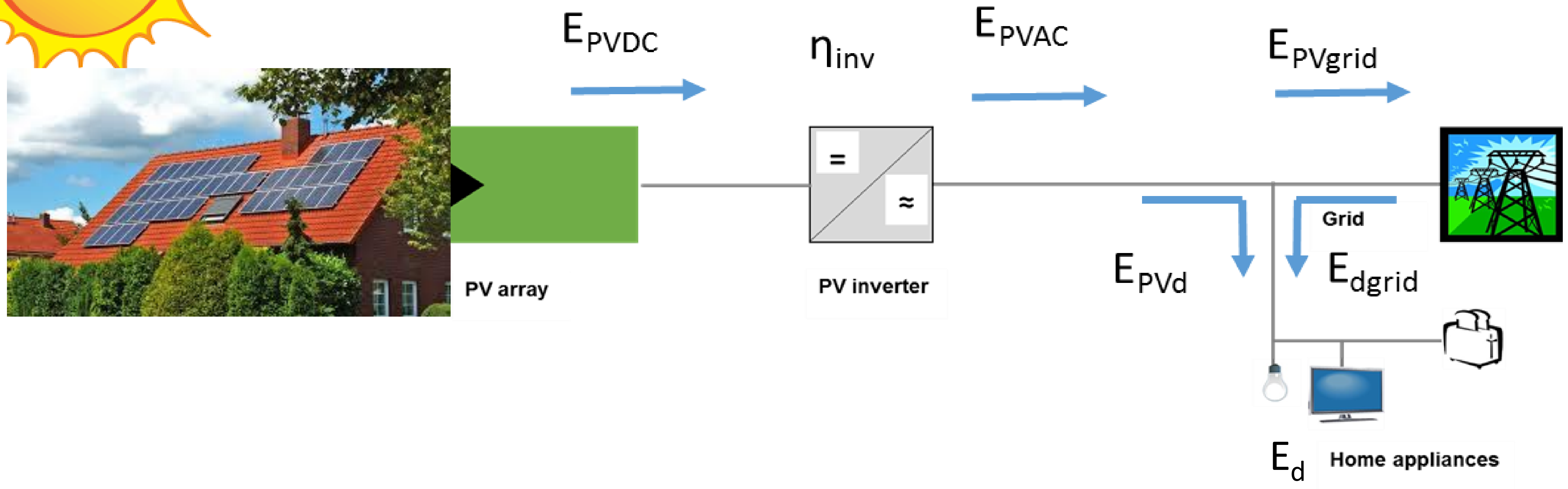
Recent Facts about Photovoltaics in Germany,

1: Fraunhofer ISE, download from http://www.pv-fakten.de,version February 21, 2018.

Battery storage costs going down



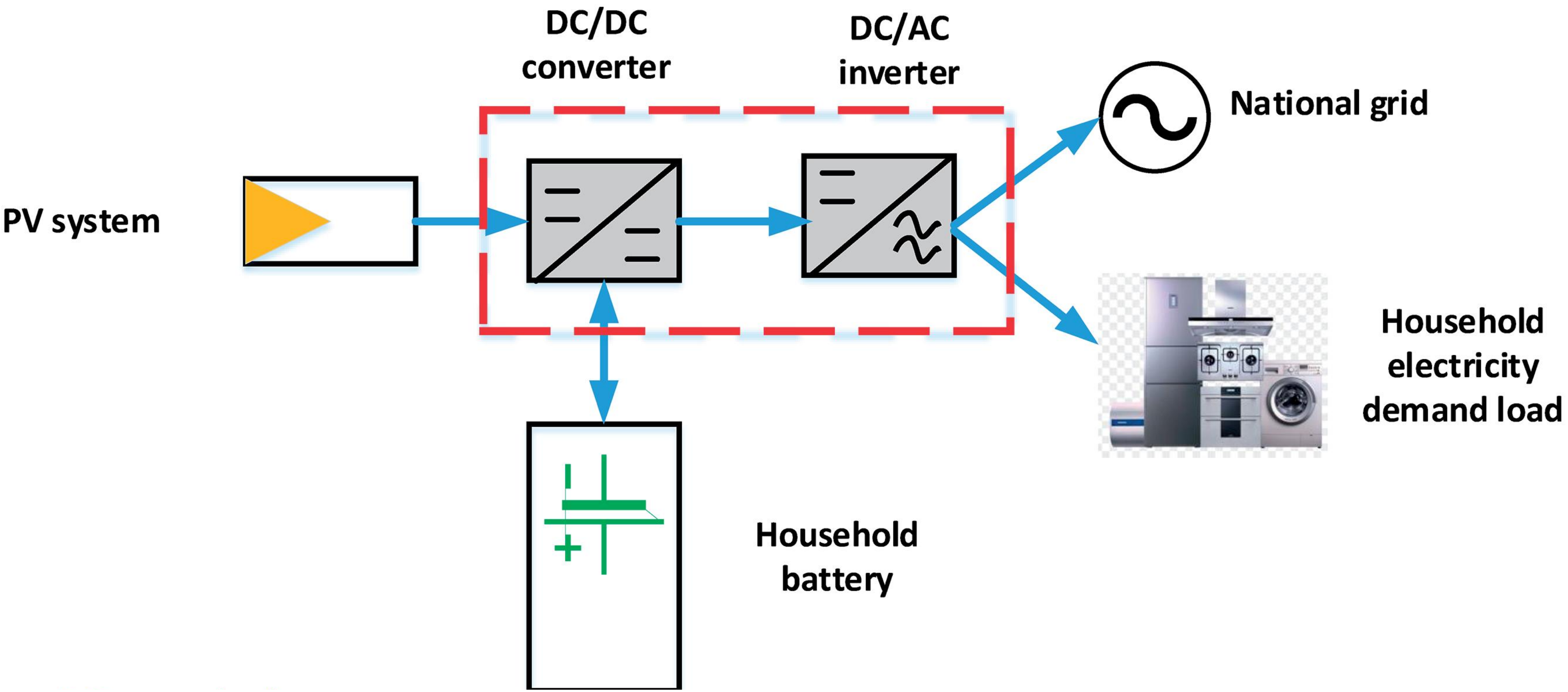
Photovolaic (PV) system



Inverter converts **DC to AC**

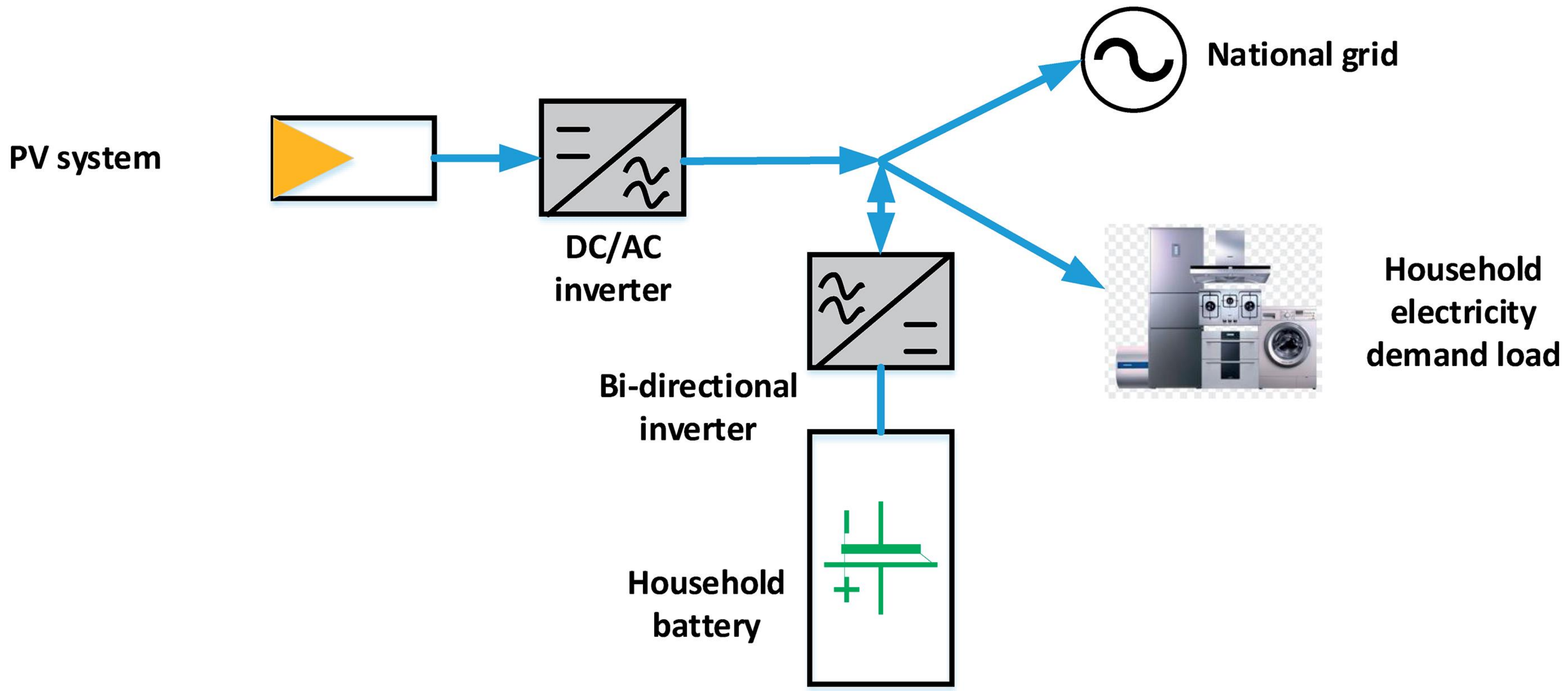
- **DC: Direct Current**
- **AC: Alternating Current AC**
- Solar panels produce DC
- Home and grid appliances use AC
- Need inverter -> causes losses
- Can still connect directly to DC side

PV DC-coupled battery system



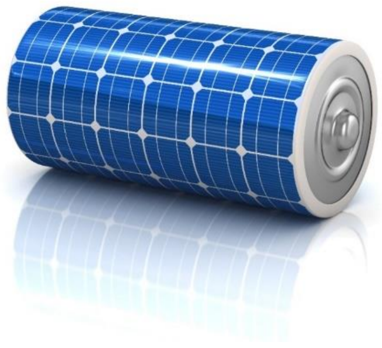
Parra (2019) Emerging market of household batteries (RSC)

PV AC-coupled battery system



Parra (2019) Emerging market of household batteries (RSC)

PV techno-economic analysis
Exercise 1



Exercise 1

- Calculate the economic indicators for a 4.8 kW_p PV system.

Input data

Input data	Value
PV nominal capacity	4.8 kW_p
Specific CAPEX of the PV system (including installation)	3000 CHF/kW_p
Specific CAPEX of the inverter	400 CHF/kW_p
Annual electricity demand	3373 kWh per year

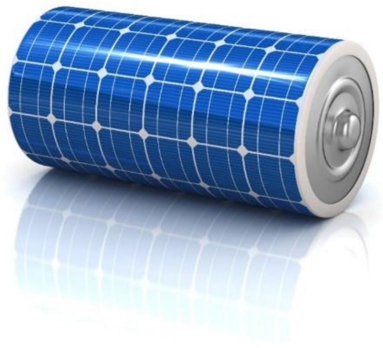
15 minute time series data provided:

- E_{PVDC} (W·h): DC PV generation
- E_d (W·h): electricity demand
- η_{inv} : DC/AC PV inverter efficiency

Outputs to calculate

- E_{PVAC} (kW·h)
- E_{PVd} (kW·h)
- E_{PVgrid} (kW·h)
- E_{dgrid} (kW·h)
- CAPEX (CHF) Capital expenditure of a 4.8 kW_p system.
- Revenue (CHF) per year.
  - The revenue is assumed to be constant over time.

Battery techno-economic analysis
Exercise 2



Exercise 2

- Study the impact of a 7 kWh battery on annual energy balance, round trip efficiency, levelised cost, levelised value and profitability using after setting up energy balances.

Input data

Input data	Value
Storage medium cost, lithium-ion (Li-ion) battery	350 CHF/kWh
Inverter and Balance of the plant (BoP)	2200 CHF/kW
Maintenance cost	0 CHF/kW

15-minute time series data for:

- E_{batd} (kW·h) AC battery discharge,
- E_{PVbat} (kW·h) AC the battery charge

1: No OPEX is assumed with the battery system
2: David Parra (2014), The University of Nottingham

Outputs to calculate

- E_{PVgrid} (kW·h): new value after the battery system is installed
- E_{dgrid} (kW·h): new value after the battery system installed
- Battery round trip efficiency[1]
- Equivalent full cycles (EFC): $(E_{dbat} x Lifetime_{bat})/Capacity_{E\_bat}$
- CAPEX (CHF): Capital expenditure.
- Revenue (CHF) per year.

1:The round trip efficiency includes all energy losses within the battery system (i.e. storage medium and battery bi-directional inverter). We will follow a "black box", approach.

Summary

- Technical and Economic indicators used to assess and compare energy options
- Energy balance requires adapting supply and demand and considering timing of both
- Prosumers – blur the line between an energy ‘producer’ and ‘consumer’
- PV with Batteries as example of Prosumer system

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QUESTIONS?

Exercises 2

Levelised cost of battery storage

$$LCOE_{ES} = \frac{CAPEX + \sum_{n=1}^{Lifetime} \frac{OPEX}{(1+r)^n}}{\sum_{n=1}^{Lifetime} \frac{E_{batd}}{(1+r)^n}}$$

CAPEX	= Capital expenditure (CHF)
OPEX	= Operational expenditure in year n (CHF)[1]
r (%)	= Discount rate (assumed to be equal to 4%)
n	= generic year
Lifetime	= durability (years)
E_{batd} (kWh)	= annual battery discharge, i.e. annual demand load met by the battery.

Exercise 2

Levelised value of battery storage

$$LVOE_{ES} = \frac{\sum_{n=1}^{Lifetime} \frac{Revenue_{bat}}{(1+r)^n}}{\sum_{n=1}^{Lifetime} \frac{E_{batd}}{(1+r)^n}}$$

- $Revenue_{bat}$ (CHF)->Revenue of the battery
- E_{batd} (kWh)->annual battery discharge, i.e. annual demand load met by the battery.