A dynamic function for the Energy Return on Investment of wind energy

Elise Dupont and Hervé Jeanmart, iMMC

elise.dupont@uclouvain.be

Motivations

- **Net energy analysis** is the best way to evaluate the **quality** and **sustainability** of an energy source, and the best indicator is the **Energy Return on Investment (EROI)**
- It is crucial to be able to **evaluate the evolution of the EROI of the future energy system,** because it will have an huge impact on our **quality of life** [1]

State of the art

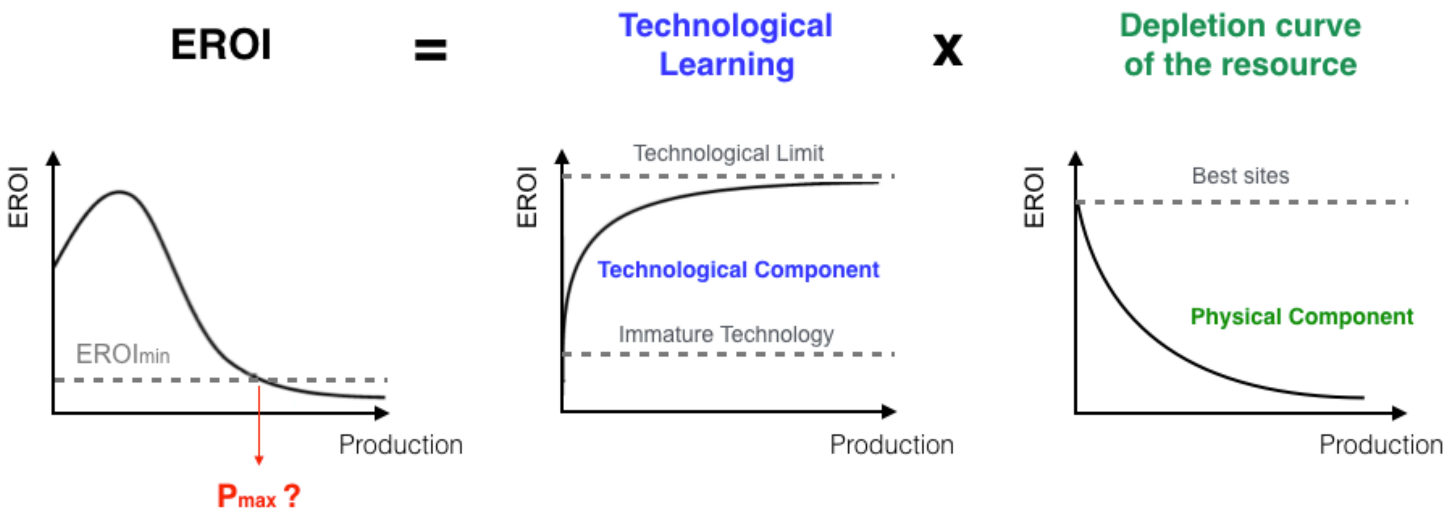
- The spread of the estimates for the technical potential of renewable energy is very wide
- Almost none of the estimates take into account net energy analysis
- Existing EROI studies are mainly static (evaluation of the EROI of a specific project at a given location)

EROI dynamics

$$\text{Energy Return On Investment} = \frac{\text{Energy Returned to Society}}{\sum \text{Energy Invested}}$$

- $EROI_{RE} << EROI_{NRE}$
- $EROI_{NRE}$ decreases with time
- $EROI_{RE}$ decreases with annual production
- $EROI_{min}$ is the minimum EROI for modern societies to support continued economic activity and social function (~ 7:1) [1]

* RE = **r**enewable **e**nergy sources, NRE = **n**on-**r**enewable **e**nergy sources



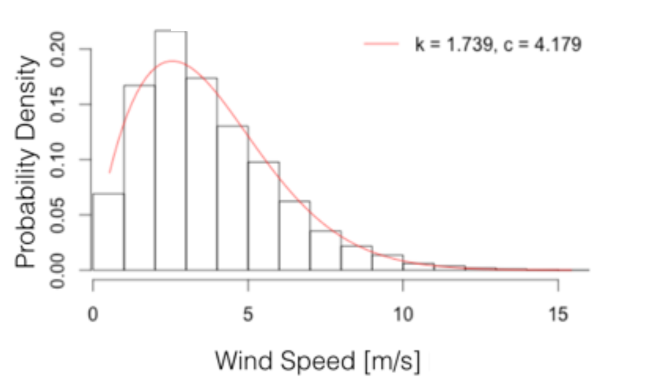
A dynamic function for the EROI, adapted from [2]

EROI function for Wind Energy : Grid-cell Approach

I. Bottom-Up Approach

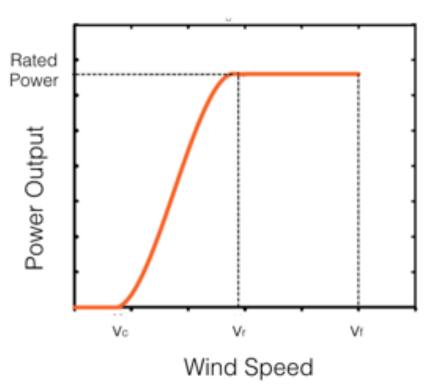
Energy Outputs

Estimate of the local parameters of the Weibull wind speed distribution

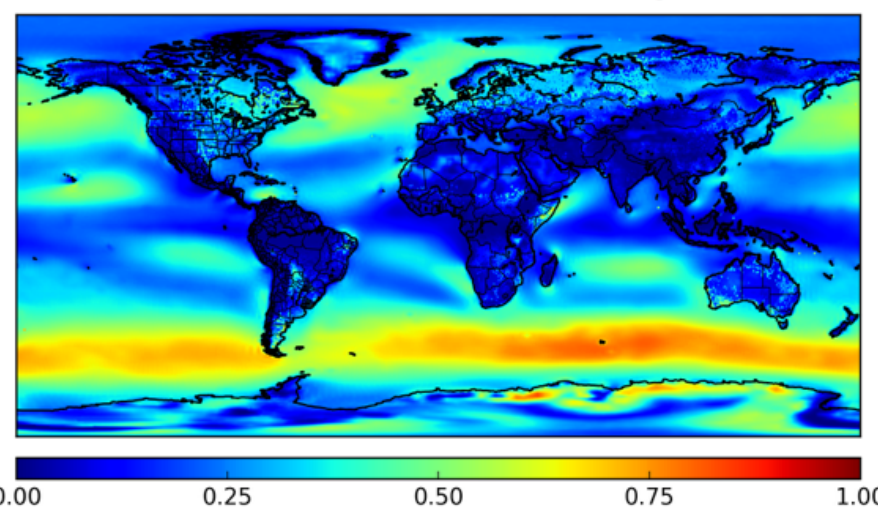


Wind speed data over 5 years on a 0.5 x 0.5° grid, from EMCWF ERA-40 project [3]

Wind turbine output parametrization



Capacity factor calculation : $C_F = \frac{1}{P_R}\int_0^{\infty} f(v)P(v)dv$



Capacity Factor (vc = 4 m/s, vr = 12 m/s, vf = 25m/s)

+ Wake effect, availability factor, transmission losses

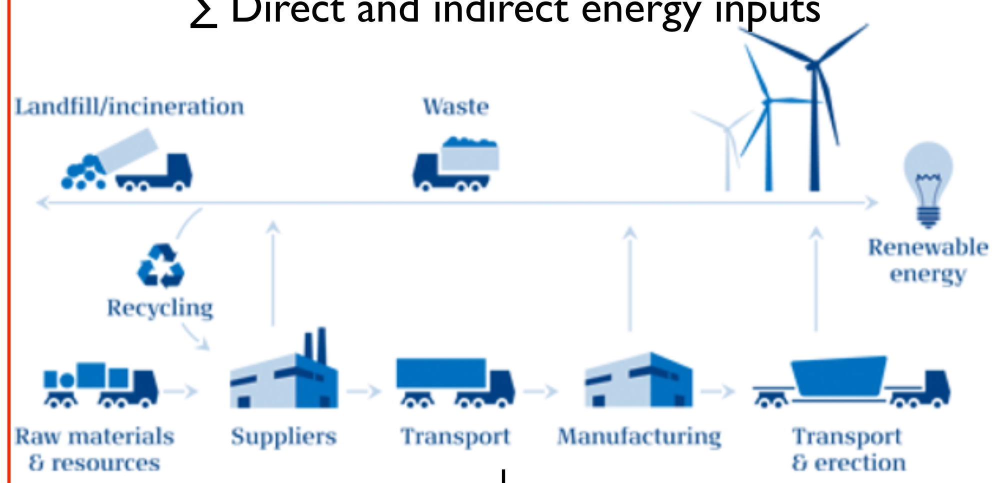
↓

Energy Generated / year / MW installed in each grid cell

Energy Inputs

Life Cycle Analysis of a wind farm

∑ Direct and indirect energy inputs

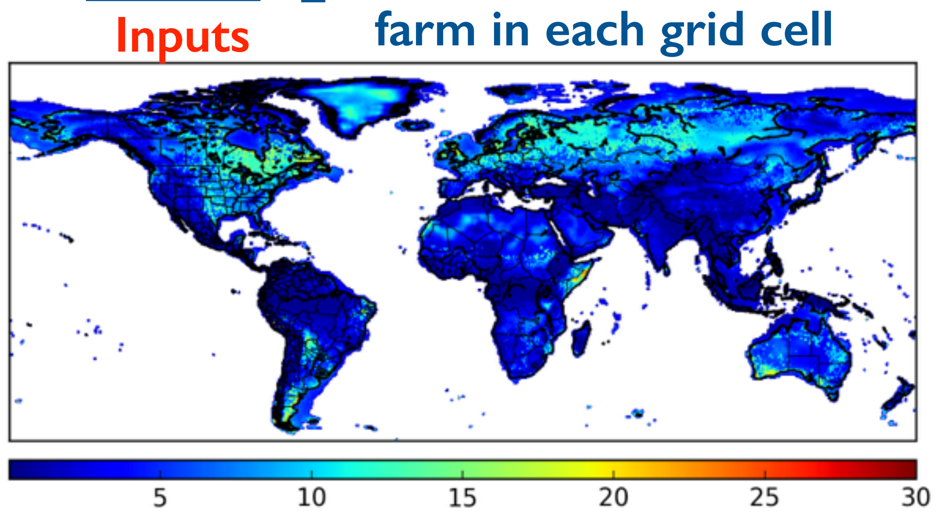


↓

Embodied Energy / MW installed

Results:
- Onshore: 15.000 GJ / MW installed
- Offshore, restricted to water depth < 200 m: 19.500 GJ / MW installed * correcting factor depending on water depth and distance to shore [4]

$$\frac{\text{Outputs}}{\text{Inputs}} = \text{EROI of standard wind farm in each grid cell}$$



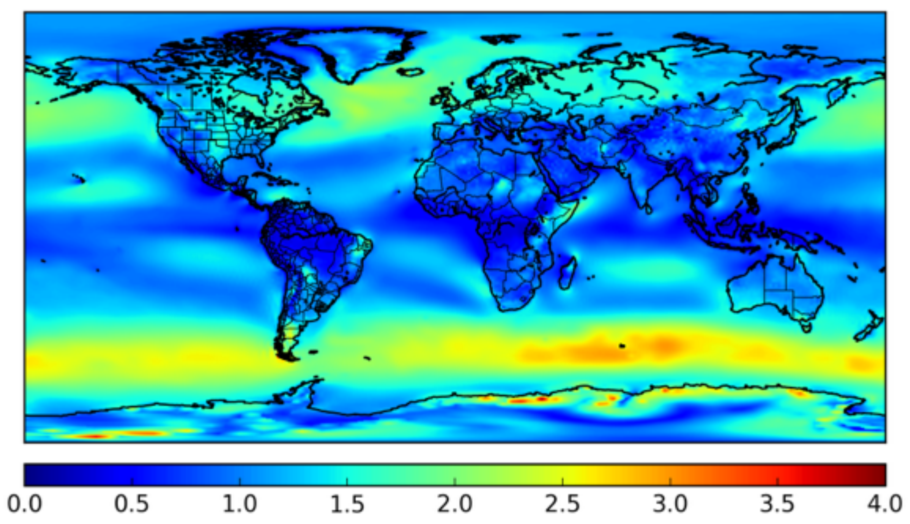
EROI

II. Top-Down Approach

Energy Conservation in ABL

In very large wind farms power extraction is limited by the vertical downward flux of kinetic energy.

Estimate of boundary layer wind dissipation with reanalysis data [3]:



Boundary layer wind dissipation [W/m²]

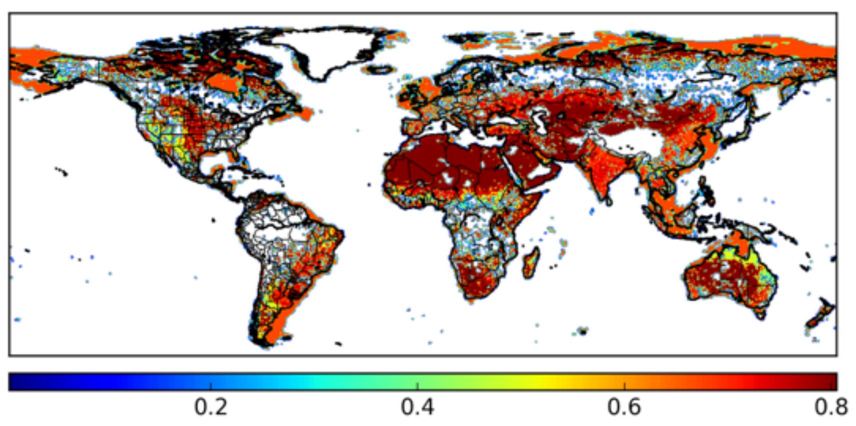
Momentum balance of the atmospheric boundary layer in steady state shows that at most **38,5 %** of this power can be extracted by wind turbines [5].

↓

Upper limit for wind power density of very large wind farms

III. Geographical Constraints

Suitability factor associated to each grid cell depending on land use [6]:



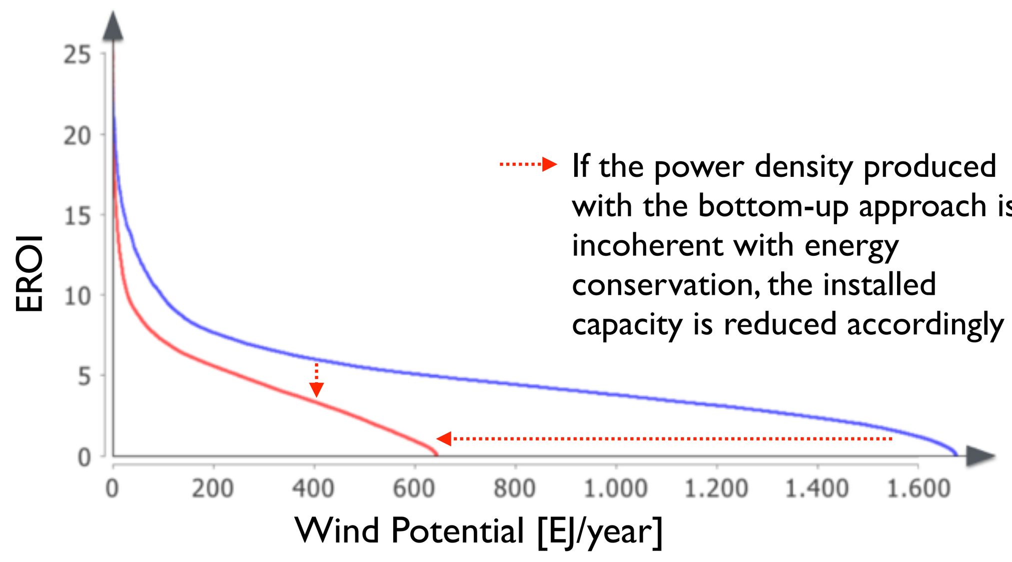
Suitability Factor [% suitable area in each cell]

- Protected areas, urban areas: 0%
- Forests: 10%
- Agricultural areas: 70%
- Barren areas: 90 %
- Offshore areas, < 200 m water depth:
  - 0 - 5 nmi from coastline : 0 %
  - 5 - 20 nmi : 33 %
  - > 20 nmi : 67 %, *nmi = nautical miles*

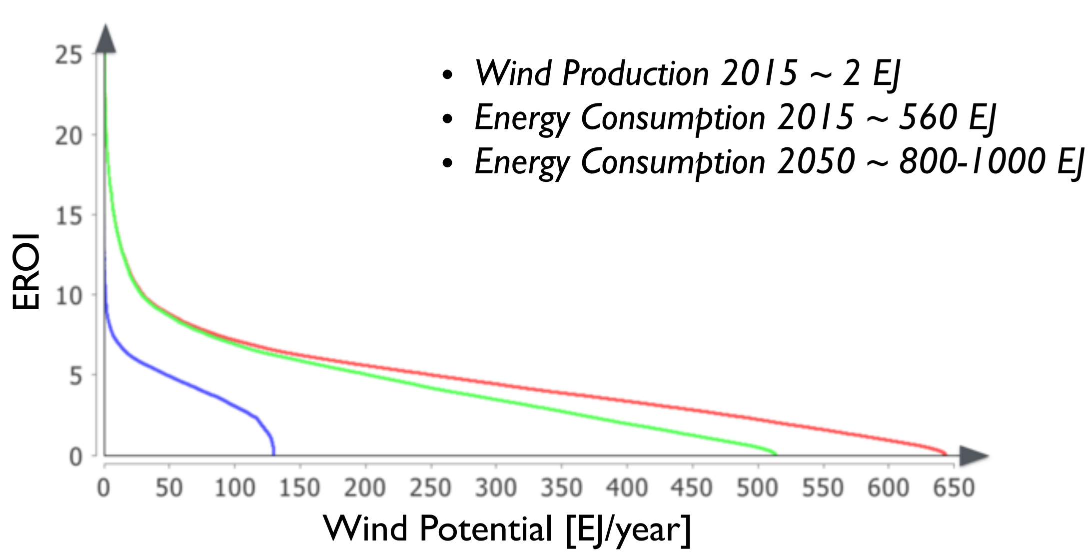
IV. Final Result - Aggregation of both approaches

I. **Bottom-up** approach gives energy generated by a wind turbine and associated EROI everywhere on earth
II. **Top-down** approach gives a limit on installed capacity density, taking into account energy conservation
III. **Geographical constraints** are added to exclude areas not suitable for wind farm installation

EROImin	Wind Potential [EJ/year]	Onshore [EJ/year]	Offshore [EJ/year]
1	594	466	128
3	432	331	101
7	108	97	11



Impact of top-down approach to bottom-up approach with capacity density of 10 MW/km²



Final result : EROI function for wind energy with geographical constraints (offshore, onshore and world total)

Future Work

- Adapt the methodology to calculate EROI function for **solar energy** and **biomass**
- Aggregate the results to model the EROI function of the future energy system
- Integrate these results in a **economic growth model**

[1] Lambert et al., Energy, EROI and quality of life, Energy Policy 64, pp. 153-167, 2014.
[2] Dale et al., A Dynamic Function for Energy Return on Investment, Sustainability 3, pp. 1972-1985, 2011.
[3] ECMWF ERA-40 Dataset : 45 years climate re-analysis dataset, http://www.ecmwf.int/research/era
[4] EEA, Europe's onshore and offshore wind energy potential, Technical Report, DOI 10.2800/11373, 2009.
[5] Miller et al., Two methods for estimating limits to large-scale wind power generation, PNAS 112, pp.11169-11174, 2015.
[6] Land cover data taken from ESA & UCL GlobCover 2009 dataset, http://due.esrin.esa.int/page_globcover.php