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The necessity for large-scale hybrid renewable energy systems

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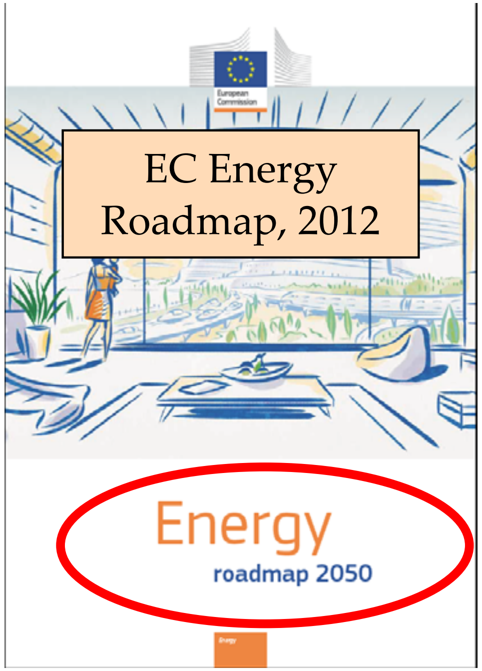
Motivation: The global energy problem and the future of renewables


NEWSFOCUS

Peak Oil Production May Already Be Here

Science, 331, 1510-1511, 2011



EC Energy Roadmap, 2012

WWF Energy Report, 2011

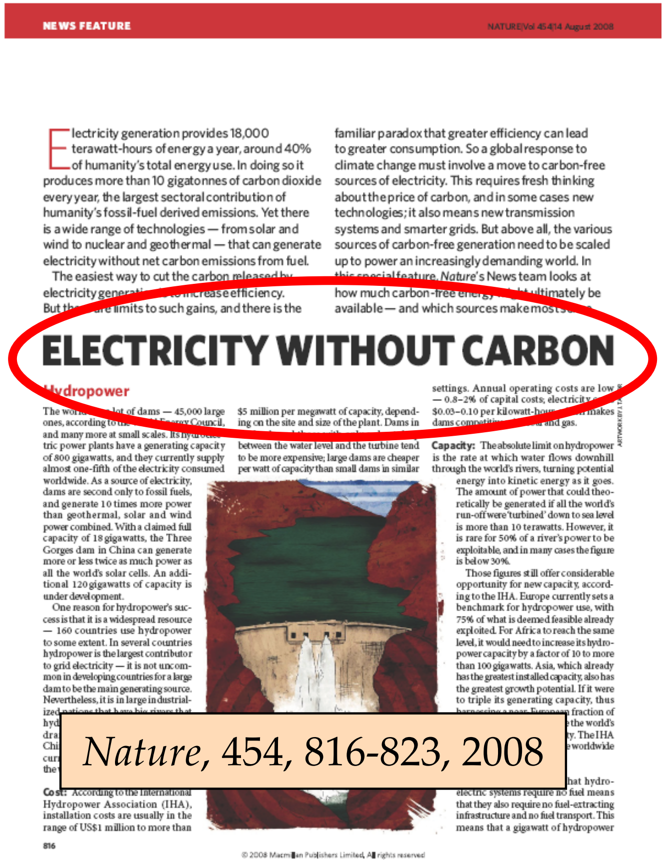
*"Outside of OPEC's vast resources, **oil production has leveled off**, and it's looking like it may never rise again.*

*[] … **even planet-scale resources have their limits**. And that when you are consuming them at close to 1000 gallons a second, the limits can catch you unaware."*

*"[In 2050] about **two thirds of our energy** should come from renewable sources… Our energy system has not yet been designed to deal with such challenges… Only a **new energy model** will make our system secure, competitive and sustainable in the long-run."*

*"By 2050, we could **get all the energy we need from renewable sources** … such a transition is not only possible but also **cost-effective**... The transition will present **significant challenges** ... There is nothing more important to our ability to create a **sustainable future**"*

Motivation: Controversial opinions on hydropower



NEWS FEATURE NATURE|Vol 454|14 August 2008

Electricity generation provides 18,000 terawatt-hours of energy a year, around 40% of humanity's total energy use. In doing so it produces more than 10 gigatonnes of carbon dioxide every year, the largest sectoral contribution of humanity's fossil-fuel derived emissions. Yet there is a wide range of technologies — from solar and wind to nuclear and geothermal — that can generate electricity without net carbon emissions from fuel.

The easiest way to cut the carbon released by electricity generati[illegible] to increase efficiency. But th[illegible] are limits to such gains, and there is the familiar paradox that greater efficiency can lead to greater consumption. So a global response to climate change must involve a move to carbon-free sources of electricity. This requires fresh thinking about the price of carbon, and in some cases new technologies; it also means new transmission systems and smarter grids. But above all, the various sources of carbon-free generation need to be scaled up to power an increasingly demanding world. In this special feature, *Nature*'s News team looks at how much carbon-free energy [illegible] ultimately be available — and which sources make most [illegible]

ELECTRICITY WITHOUT CARBON

Hydropower

The wor[illegible] lot of dams — 45,000 large ones, according to the [illegible] Energy Council, and many more at small scales. Its hydroelectric power plants have a generating capacity of 800 gigawatts, and they currently supply almost one-fifth of the electricity consumed worldwide. As a source of electricity, dams are second only to fossil fuels, and generate 10 times more power than geothermal, solar and wind power combined. With a claimed full capacity of 18 gigawatts, the Three Gorges dam in China can generate more or less twice as much power as all the world's solar cells. An additional 120 gigawatts of capacity is under development.

One reason for hydropower's success is that it is a widespread resource — 160 countries use hydropower to some extent. In several countries hydropower is the largest contributor to grid electricity — it is not uncommon in developing countries for a large dam to be the main generating source. Nevertheless, it is in large industrialized [illegible]

Cost: According to the International Hydropower Association (IHA), installation costs are usually in the range of US$1 million to more than $5 million per megawatt of capacity, depending on the site and size of the plant. Dams in [illegible] between the water level and the turbine tend to be more expensive; large dams are cheaper per watt of capacity than small dams in similar settings. Annual operating costs are low — 0.8–2% of capital costs; electricity [illegible] $0.03–0.10 per kilowatt-hour, [illegible] makes dams competiti[illegible] and gas.

Capacity: The absolute limit on hydropower is the rate at which water flows downhill through the world's rivers, turning potential energy into kinetic energy as it goes. The amount of power that could theoretically be generated if all the world's run-off were 'turbined' down to sea level is more than 10 terawatts. However, it is rare for 50% of a river's power to be exploitable, and in many cases the figure is below 30%.

Those figures still offer considerable opportunity for new capacity, according to the IHA. Europe currently sets a benchmark for hydropower use, with 75% of what is deemed feasible already exploited. For Africa to reach the same level, it would need to increase its hydropower capacity by a factor of 10 to more than 100 gigawatts. Asia, which already has the greatest installed capacity, also has the greatest growth potential. If it were to triple its generating capacity, thus harnessing a near-European fraction of [illegible] the world's [illegible]ty. The IHA [illegible] worldwide [illegible] hat hydroelectric systems require no fuel means that they also require no fuel-extracting infrastructure and no fuel transport. This means that a gigawatt of hydropower

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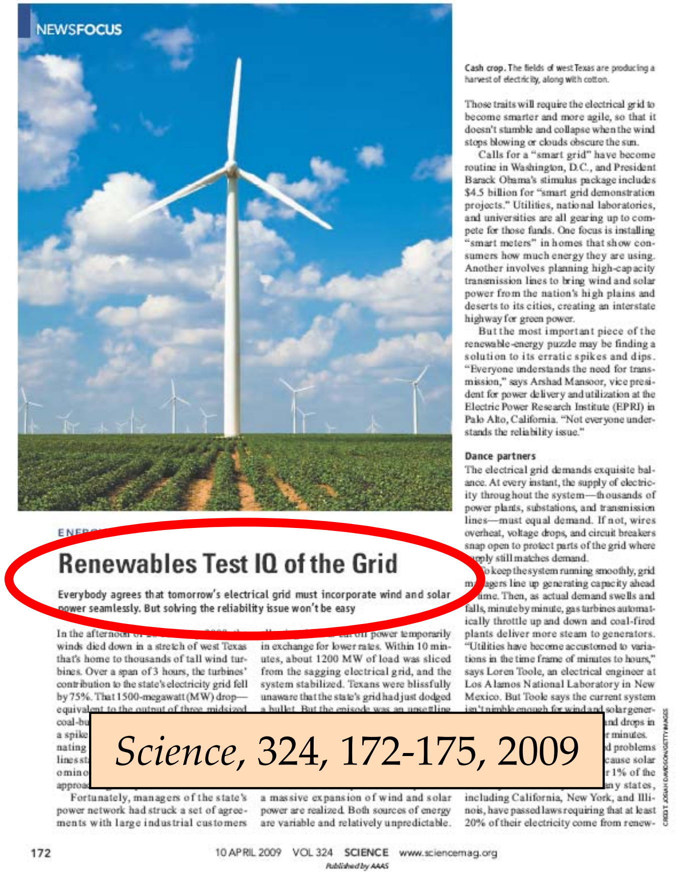
Nature, 454, 816-823, 2008



NEWSFOCUS

Cash crop. The fields of west Texas are producing a harvest of electricity, along with cotton.

Renewables Test IQ of the Grid

Everybody agrees that tomorrow's electrical grid must incorporate wind and solar power seamlessly. But solving the reliability issue won't be easy

In the afternoon [illegible] 2008, the winds died down in a stretch of west Texas that's home to thousands of tall wind turbines. Over a span of 3 hours, the turbines' contribution to the state's electricity grid fell by 75%. That 1500-megawatt (MW) drop—equivalent to the output of three midsized coal-bu[illegible]

Fortunately, managers of the state's power network had struck a set of agreements with large industrial customers [illegible] power temporarily in exchange for lower rates. Within 10 minutes, about 1200 MW of load was sliced from the sagging electrical grid, and the system stabilized. Texans were blissfully unaware that the state's grid had just dodged a bullet. But the episode was an unsettling [illegible] a massive expansion of wind and solar power are realized. Both sources of energy are variable and relatively unpredictable. Those traits will require the electrical grid to become smarter and more agile, so that it doesn't stumble and collapse when the wind stops blowing or clouds obscure the sun.

Calls for a "smart grid" have become routine in Washington, D.C., and President Barack Obama's stimulus package includes $4.5 billion for "smart grid demonstration projects." Utilities, national laboratories, and universities are all gearing up to compete for those funds. One focus is installing "smart meters" in homes that show consumers how much energy they are using. Another involves planning high-capacity transmission lines to bring wind and solar power from the nation's high plains and deserts to its cities, creating an interstate highway for green power.

But the most important piece of the renewable-energy puzzle may be finding a solution to its erratic spikes and dips. "Everyone understands the need for transmission," says Arshad Mansoor, vice president for power delivery and utilization at the Electric Power Research Institute (EPRI) in Palo Alto, California. "Not everyone understands the reliability issue."

Dance partners

The electrical grid demands exquisite balance. At every instant, the supply of electricity throughout the system—thousands of power plants, substations, and transmission lines—must equal demand. If not, wires overheat, voltage drops, and circuit breakers snap open to protect parts of the grid where supply still matches demand.

To keep the system running smoothly, grid managers line up generating capacity ahead of time. Then, as actual demand swells and falls, minute by minute, gas turbines automatically throttle up and down and coal-fired plants deliver more steam to generators. "Utilities have become accustomed to variations in the time frame of minutes to hours," says Loren Toole, an electrical engineer at Los Alamos National Laboratory in New Mexico. But Toole says the current system isn't nimble enough for wind and solar gener[illegible] and drops in [illegible] minutes. [illegible] problems [illegible] cause solar [illegible] 1% of the [illegible] any states, including California, New York, and Illinois, have passed laws requiring that at least 20% of their electricity come from renew-

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Greenpeace International
& European Renewable
Energy Council, 2010

energy
[r]evolution

A SUSTAINABLE WORLD ENERGY OUTLOO

EREC EUROPEAN RENEWABLE ENERGY COUNCIL

GREENPEACE

report 3rd edition 2010 world energy scenario

*"The easiest way to cut the carbon released by electricity generation is to increase **efficiency**… **Hydroelectric systems are unique** among generating systems in that they can … **store the energy** generated elsewhere."*

*"Everybody agrees that tomorrow's electrical grid must incorporate wind and solar power seamlessly. But solving the **reliability issue** won't be easy… **The ideal dance partner is hydroelectric power**."*

*"Hydropower is a mature technology with a **significant part of its global resource already exploited**. There is still … some potential left … for new schemes (especially **small scale run-of-river projects with little or no reservoir impoundment**)"*

Autonomy through renewables: Fact or fiction?

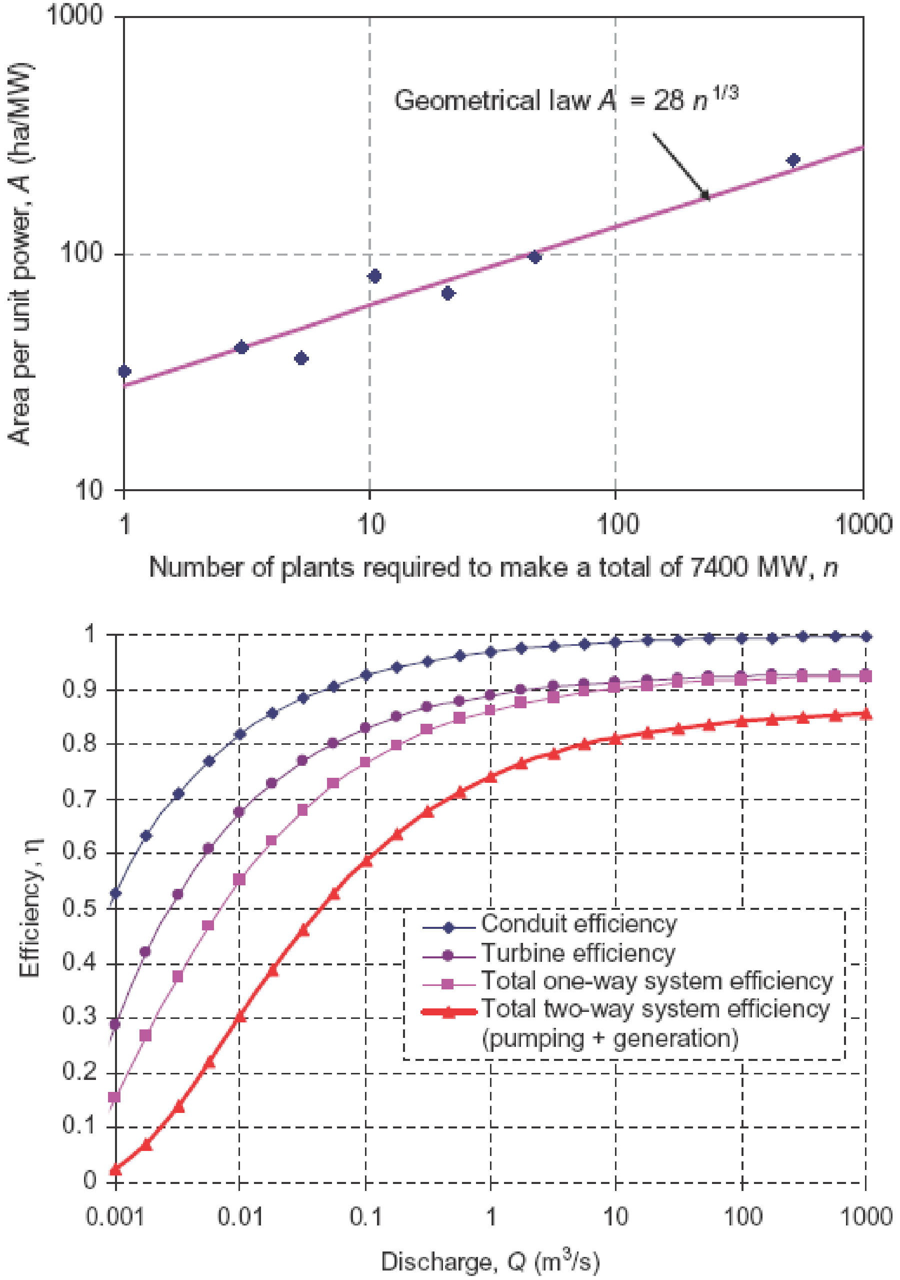
- **The fiction**
  - A fully controllable and deterministically manageable energy production via renewables is feasible, similarly to the past model based on fossil fuels.
  - A major shift from fossil fuels to renewables will be beneficial for both the economy and the environment.
- **The facts**
  - Fossil fuels are limited in quantity.
  - Renewable energy sources are not predictable neither controllable, at both the short and long run.
  - The variability of the renewable energy production cannot follow the corresponding demand.
  - Until now, the experience with "green development", in terms of macro-economic results, is rather disappointing.
  - Management of renewable energy sources on an individual project basis results in considerable over-sizing.
  - Renewables look environmental-friendly but negative impacts are inevitable.

The multiple role of water within hybrid systems

- **Water as energy transformer (producer & consumer)**
  - Direct producer, as the means for hydroelectricity generation;
  - Indirect producer, as essential element of the biofuel industry;
  - Consumer, in case of pumping.
- **Water as energy buffer (storage)**
  - Pumping water to an upstream location, taking advantage of the excess of energy (e.g. during night hours), and next retrieving this water to generate hydropower, is the unique means for energy storage at large scale;
  - Pumped storage is a proven technology with very high efficiency (>90%, for large flows).
- **Hybrid renewable energy systems (HRES)**
  - Generally, hybrid energy systems refer to the mixing of different sources or technologies that, when integrated, overcome limitations inherent in either;
  - Such systems are well-tested at small spatial scales, e.g. to serve autonomous island grids;
  - In the present context, HRES refer to combined schemes of wind/solar and pumped storage plants.

The scale issue

- Scale refers to both the **size of energy units** and their **spatial extent**.
- **Efficiency**, in terms of average energy production to installed capacity, increases with scale.
- **Safety**, in terms of fulfilling energy demand, increases with scale.
- **Cost**, in terms of initial investment and maintenance of the related infrastructures, decreases with increased scale.



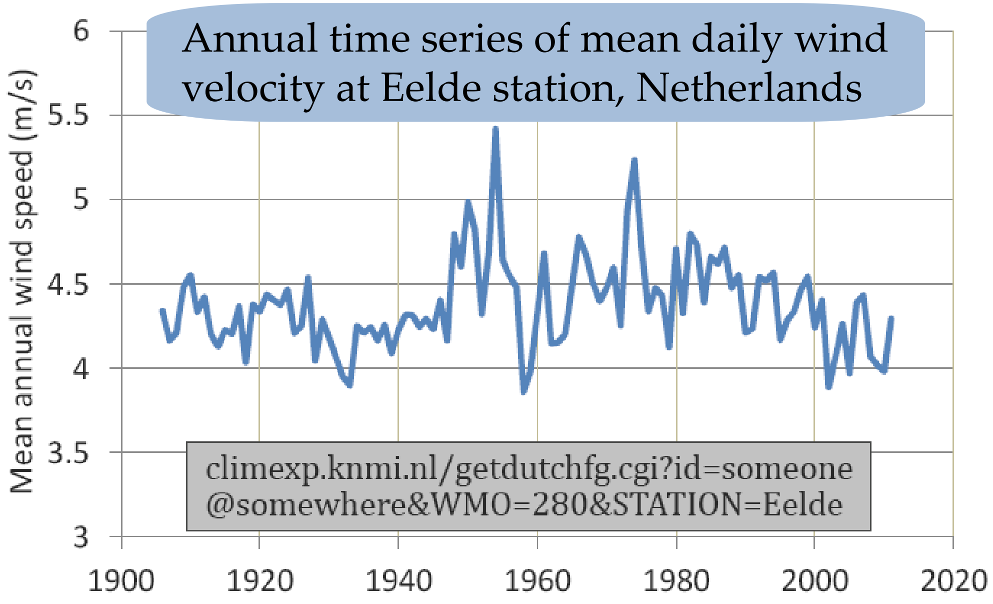
Upper panel: Graphical depiction of reservoir area per unit power vs. number of plants required to make a total of 7400 MW;
Lower panel: Partial and total efficiency of a hypothetical pumped-storage plant vs. discharge
(Source of figures: Koutsoyiannis, 2011)

Transferable lessons from water management: The concept of sustainability

- A water management practice is characterized sustainable if it ensures **enough water** to satisfy the various **demands** (by means of uses and constraints**)**, not only at the present moment but on a **long-term horizon**.
- Water is sustainable by nature (grace to the eternal hydrological cycle), yet a **water management policy** may be strongly unsustainable.
- In this context, the concept of sustainability has two equally important aspects, the availability of resources, which is **controlled by nature**, and their management, which is **human-driven**.
- Renewable energy sources, including hydropower, wind, wave, tidal and biofuels, are all based on **solar energy**, which is by definition sustainable.
- Although renewables are naturally sustainable (i.e. energy supply never stops), lack of a **regulating mechanism** makes them strongly unsustainable, from the real time energy-management perspective.
- The role of this mechanism should be assigned to **large-scale pumping-storage plants**, which will play the same role with **large-scale reservoirs** in water resources management.

Transferable lessons from water management: The concept of uncertainty

- Uncertainty is intrinsic in both the water and renewable energy management, since **predictions of the water and energy production**, based on deterministic modelling of the related hydrometerological processes, are impossible.
- Hydrologists are **familiar** with uncertainty concepts, since all hydraulic structures are designed for a specified level of risk, while a key objective in water resources management is the minimization of risk for water shortage.
- A stochastic-entropic theory of processes provides a powerful framework for the **quantification of uncertainty** within the water and energy production.
- A key issue in both the design and management of HRES is the consistent representation of the statistical behaviour of the related physical processes at all time scales – especially at the large scale (annual and over-annual), in which the **Hurst-Kolmogorov behaviour** dominates.


Annual time series of mean daily wind velocity at Eelde station, Netherlands

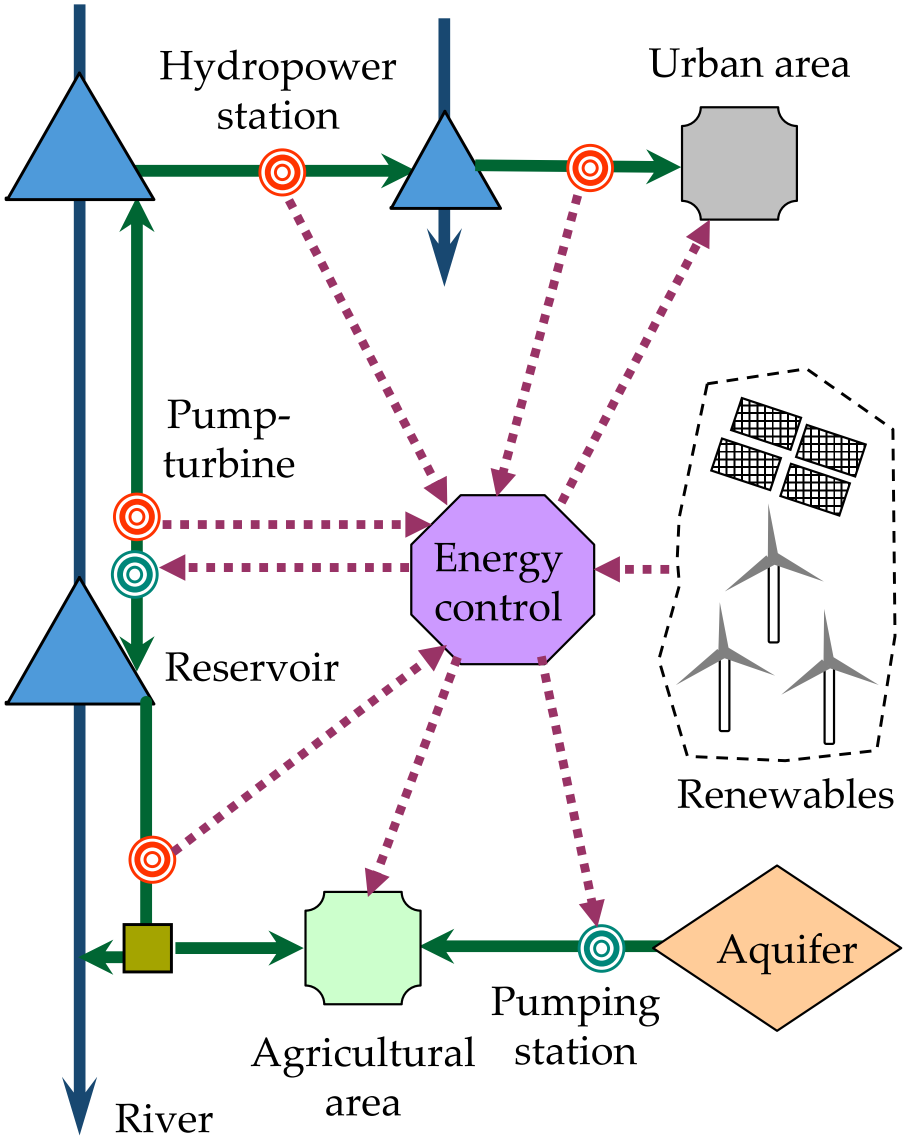
climexp.knmi.nl/getdutchfg.cgi?id=someone@somewhere&WMO=280&STATION=Eelde

Transferable lessons from water management: The concept of reliability

- The reliability of a system is generally defined as the **probability** that the system will perform the required function for a specific period of time under stated conditions (Koutsoyiannis, 2005).
- Uncertainty and reliability are two closely related concepts in water and energy management; the former refers to the **randomly varying production**, while the later refers to the **regularly varying demand**.
- Reliability is typically expressed either as an **external constraint**, imposed by the system "manager", or an **objective** to maximize.
- The amount of water that can be ensured with an acceptable reliability level is generally called **safe yield**; in the case of **hydroelectric reservoirs**, the amount of energy that is generated with very high reliability is called **firm energy**.
- The same concept should be extended to large-scale renewable energy systems, given that the design of a HRES depends on the uncertainty of inflows and the desirable reliability level to fulfil the energy demand.
- If we seek **full autonomy** through renewables, an almost 100% reliability should be imposed, which may be infeasible or economically inefficient.

Transferable lessons from water management: The concept of optimality

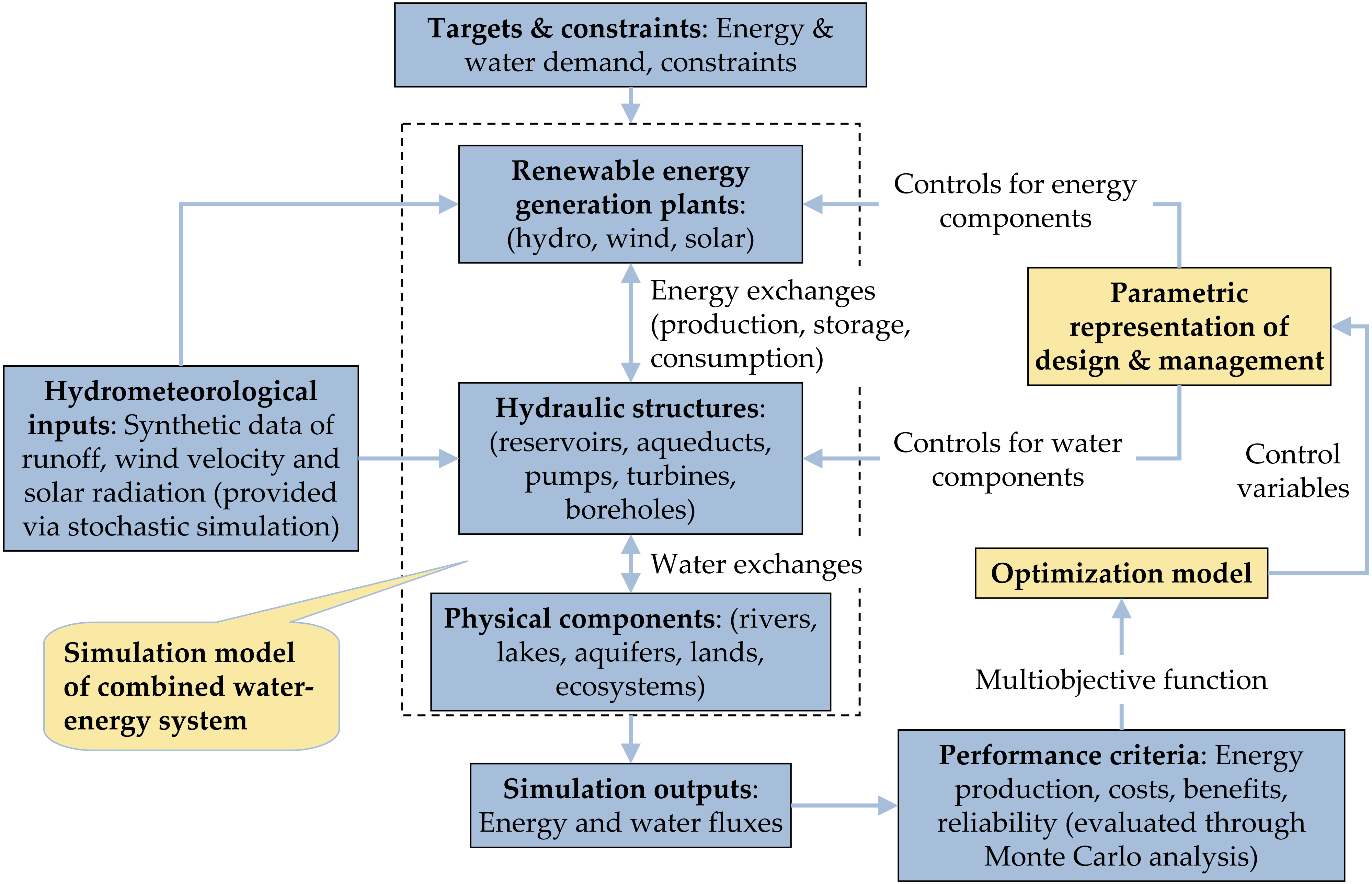
- In water resource systems, several **optimization** problems can be formulated, for a given hydroclimatic regime and a given set of constraints:
  - Optimization of the **configuration & sizing** of the system, to ensure the desirable reliability with minimal cost;
  - Maximization of the **long-term performance** (in terms of safe yield, mean economic benefit, firm energy, etc.) of an existing hydrosystem;
  - Optimization of the **short-term operation policy** of the system, to fulfil the specific uses with low risk.
- Similar questions are applicable to HRES, the design and management of which requires a **systems-based approach**.



Transferable lessons from water management: The parameterization-simulation-optimization approach

- Typical drawbacks, common in water and renewable energy modelling:
  - large number of **decision variables** (i.e. unknown fluxes) and **constraints**;
  - nonlinearity of **system dynamics**;
  - uncertainty of future **inflows** and **demands**;
  - competitive or even conflicting **objectives**.
- Key concepts within the parameterization-simulation-optimization framework (Koutsoyiannis & Economou, 2003), also applicable to HRES:
  - generation of synthetic inputs, either unconditional or conditioned for prediction, derived through **multivariate stochastic models**;
  - low-dimensional representation of the main system controls, through **parsimonious parameterizations** (e.g. in terms of operation rules);
  - faithful representation of system dynamics, accounting for the **physical constraints**, the **priorities** of demands and the **operational costs**;
  - probabilistic evaluation of all water and energy fluxes and quantification of uncertainties, through **Monte-Carlo simulation**;
  - use of **multicriteria optimization** to provide rational results.

Combined modelling of water & energy resources



Targets & constraints: Energy & water demand, constraints

Renewable energy generation plants: (hydro, wind, solar)

Controls for energy components

Parametric representation of design & management

Energy exchanges (production, storage, consumption)

Hydrometeorological inputs: Synthetic data of runoff, wind velocity and solar radiation (provided via stochastic simulation)

Hydraulic structures: (reservoirs, aqueducts, pumps, turbines, boreholes)

Controls for water components

Control variables

Water exchanges

Optimization model

Simulation model of combined water-energy system

Physical components: (rivers, lakes, aquifers, lands, ecosystems)

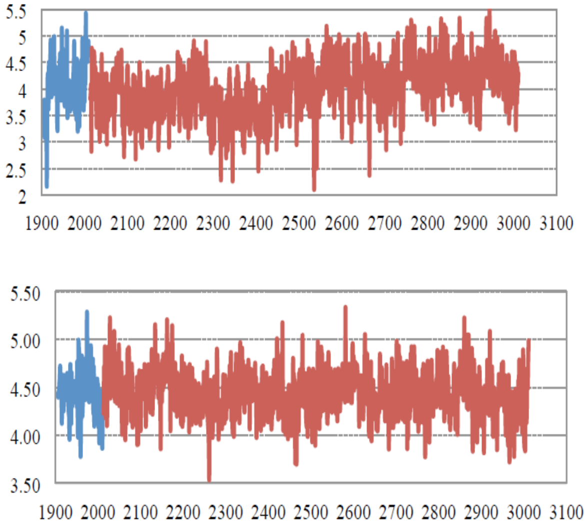
Multiobjective function

Simulation outputs: Energy and water fluxes

Performance criteria: Energy production, costs, benefits, reliability (evaluated through Monte Carlo analysis)

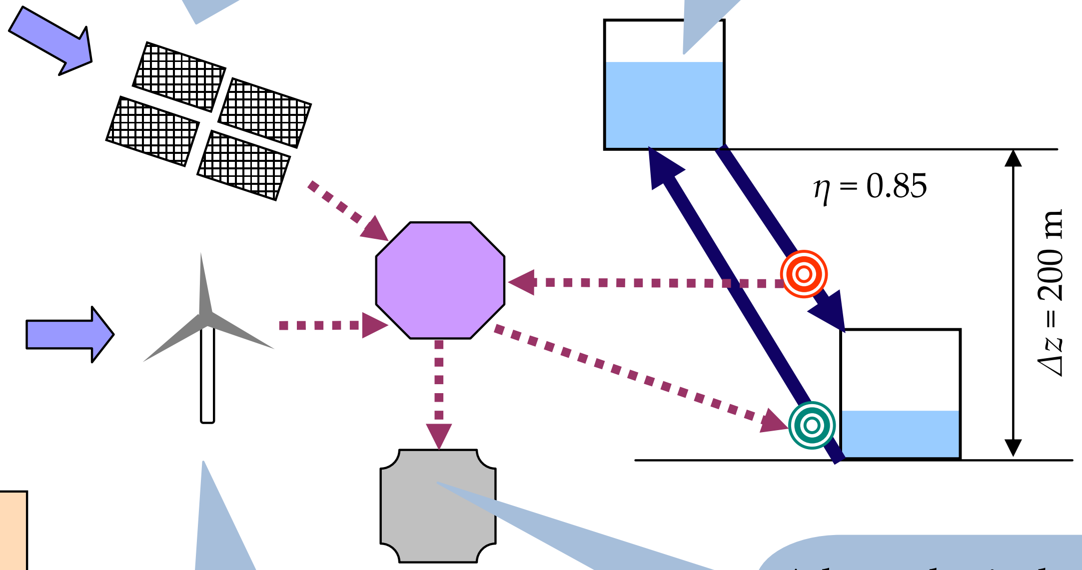
A toy-system example

Synthetic time series of mean daily sunshine duration and wind velocity, with Hurst coefficients H_s and H_w (Tsekouras, 2012)



n_s solar panels, with known characteristics (angle, maximum power, efficiency)

Pumping-storage system, with known efficiency, comprising two similar tanks of capacity k, at given elevations



Problem statement, for various combinations of H_s, H_w and P (Ioannou, 2012):

minimize cost = $f(n_s, k)$

s.t. failure probability < 100 days in 500 simulated years

Commercial wind tower of significant capacity (Enercon E-126, 7.5 MW)

A hypothetical city of population P, with known energy demand, for a control period of 500 years (182 500 days)

Conclusions

- The optimal planning and management of **renewable energy** is a necessity for ensuring a **sustainable future**.
- The key challenge is the transformation of the highly varying **natural sources of energy**, which are associated with **uncertain** and **unpredictable** hydrometerological processes, into **regular energy outflows** that satisfy the corresponding demands, at multiple time scales.
- In the near future scene, **water** will have multiple roles, as the means of producing, consuming and storing energy within **large-scale hybrid renewable energy systems**.
- **Hydropower** and **pumping** will be the common components of combined water and the energy systems (outputs of the former, inputs of the latter).
- In this context, advanced modelling concepts and tools are essential, based on the broad **experience from water management**.
- The **parameterization-simulation-optimization** framework is a powerful approach of general applicability, which recognizes and incorporates the key concepts of **uncertainty**, **reliability** and **optimality**, and provides rational and sustainable solutions to design and management problems of high complexity, with reasonable computational effort.

A rejection story on funding attempts

- **March 2008**: Climate, Hydrology, Energy, Water: the Conversion of Uncertainty Domination and Risk Into Sustainable Evolution (CHEWtheCUDandRISE)
  - Research proposal submitted for the 2008 ERC grand
  - Outcome: Rejection
  - Summary published as opinion paper in HESS (Koutsoyiannis *et al.*, 2009)
- **March 2010**: WATer pathways towards the non-deterministic future of renewable enERGY (WATERGY)
  - Research proposal submitted for the 2010 ERC grand
  - Outcome: Rejection
- **September 2010**: Alternative Robust Energy Technologies for Environmental Sustainability (ARETES)
  - Research proposal submitted for the ARISTEIA I grand
  - Outcome: Rejection
- **June 2012**: Combined REnewable Systems for Sustainable ENergy DevelOpment (CRESSENDO)
  - Research proposal submitted for ARISTEIA II grand
  - Outcome: Uncertain

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This presentation is available on-line at:

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You are kindly invited to visit poster session POWER

A. Efstratiadis, D. Bouziotas, & D. Koutsoyiannis:

"The parameterization-simulation-optimization framework for the management of hydroelectric reservoir systems"

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