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$$H\cdot(\nabla\times E)=\nabla\cdot(E\times H)+E\cdot(\nabla\times H)$$

$$H\cdot\left(-\frac{\partial B}{\partial t}\right)=\nabla\cdot(E\times H)+E\cdot\left(j+\frac{\partial D}{\partial t}\right)$$

$$E\cdot\left(\frac{\partial D}{\partial t}\right)=\frac{\partial\left(\varepsilon E^2/2\right)}{\partial t}$$

$$H\cdot\left(\frac{\partial B}{\partial t}\right)=\frac{\partial\left(B^2/2\mu\right)}{\partial t}$$

Renewable Sources

-

Basics, Wave, Underwater currents, Wind and Hydropower

$$\oint_S (E\times H)\cdot da+\int_V j\cdot E\,d\tau=-\frac{\partial}{\partial t}\int_V\left(\frac{\varepsilon E^2}{2}+\frac{B^2}{2\mu}\right)d\tau$$

Prof Mats Leijon

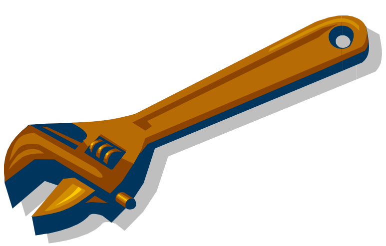
Dept of Engineering Science

Swedish Centre for Renewable Electric Energy Conversion

Swedish Hydropower Centre

Uppsala University

Sweden



Introduction to Electricity Uppsala

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7 supervisors (3prof,3ass.prof,1adj.prof)
5 seniors
22 PhD students
2 fullscale labs

- Strategic resp. for technical education at UU
- Resp. for program – engineering science at UU
- Main base cources (around 60 hst/year)
  Hydropower, Windpower, Wavepower
  Power Engineering, Circuit theory, Electronics, Environmental Technology, EMC, Fluid Mechanics
- Hydropower masterprogram together with LTU

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Ongoing research

Wavepower 5 PhD

Windpower 3 PhD

Marine Currents 2 PhD

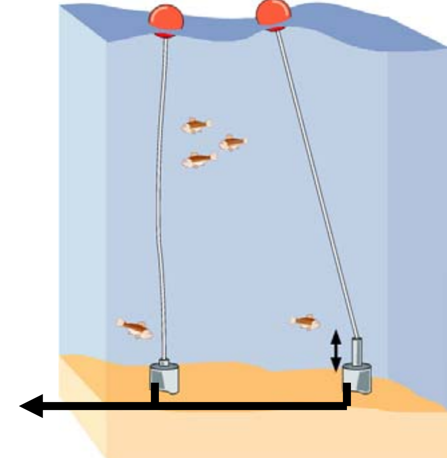
Biofuelled plants 2 PhD

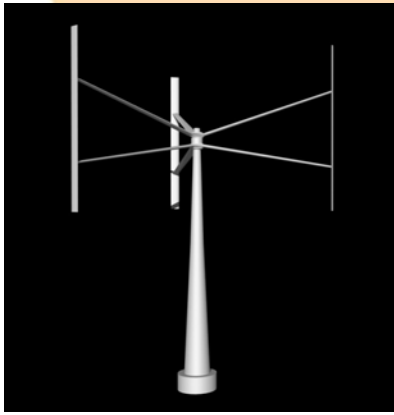
Hydropower 2 PhD

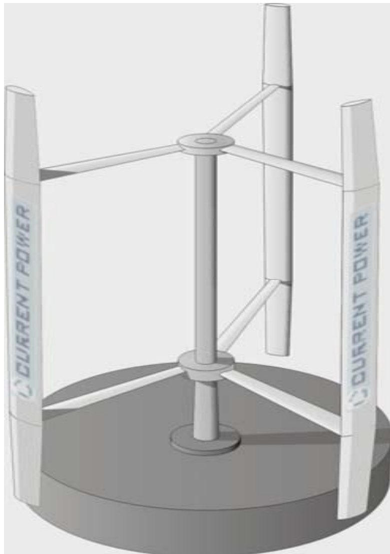
Plasma Physics 2 PhD

EMC 3 PhD

Lightning 3 PhD







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Energy - Power

W=UI*t

Not used as regulation

Most sources

P=UI

Short time regulation

Hydro

Gas-turbines

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Economy for a power plant

Cost

Is driven by installed **power (MW)**

Compare with a car…

Income

Is set by converted **energy (MWh)**

A taxi-owner wants 24h operation at full rate….

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Why do we want to boil water ?

A. Sources having high power density (Coal/Oil/Nuclear)

i.e. Power density (kW/m, kW/m2 or kW/m3)

B. The steam turbine works 24h all days - the whole year….

i.e. Large number of full operational hours /year

…. **Payback of the installed power**….

Power Management

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Converting this into "renewable" leads to…

…examination of the physics of the different sources…

…but - with no fuel costs.

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Power Density (kW/m^2)

In natural time-varying sources the power density varies

A Extreme values – sets extreme design values.

B Yearly average values - sets power ratings.

Max sun power density (in Sweden) is almost equal to a wind power density at 11 m/s – 1 kW/m^2

Underwater streams at 2m/s gives a power density of 4 kW/m^2

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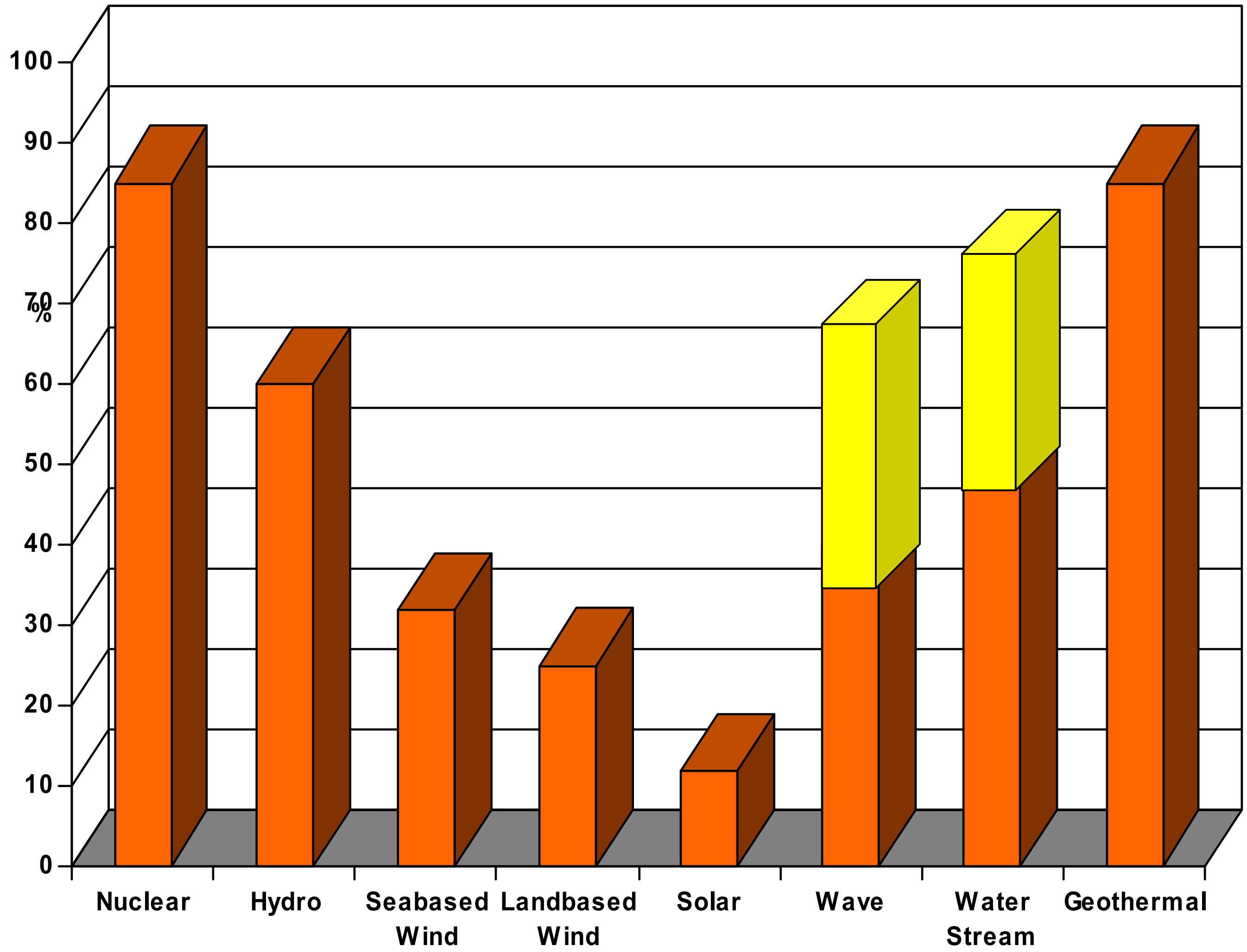
Utilization (W/P8760)

Annual production/Installed power times number of hours/year



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Net present value calculation for some renewable sources.

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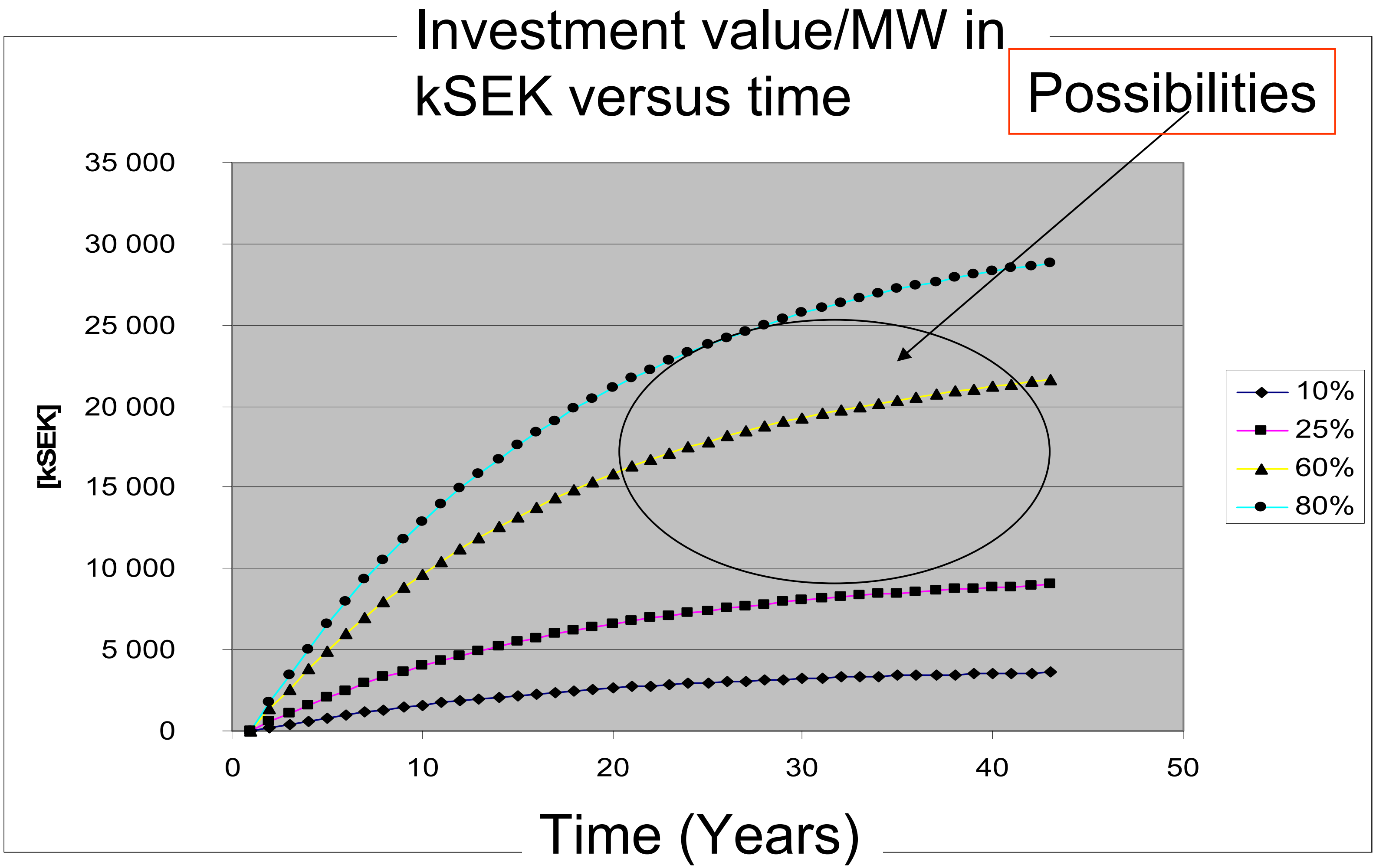

Production price ~ 30 öre/kWh or almost 3 Eurocent/kWh

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Renewable sources

Adapt technology to nature

- Economy
- Ecology
- Technology

In practice…

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Converting Physics into Technology….

…is a major challenge…

…but it can be done

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Comparison…

Source	Power Density (kW/m^x)	Utilization (h/year)	Efficiency (%)	Value* Euro/Year•m^x
Sun				
Wind				
Wave				
UW				

* Multiply by the production price set by EU 6FP for 2020 ~ 5 Eurocent

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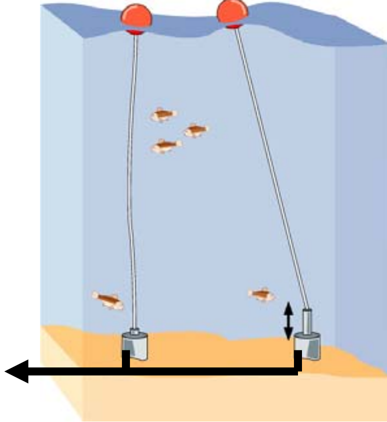
Conclusion



Renewable sources having:

A High power density

B High number of full load hours / year

C No fuel cost

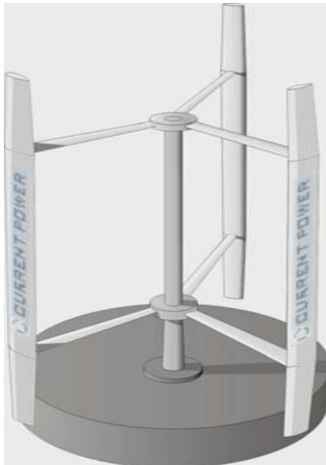
… has large possibilities to be economically competetive in the future…

Examples are…

A Geothermal

B Underwater streams

C Waves



… if we today have no or poor technological solutions…opens possibilities…

… since it is the only part we as humans can change…

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Now over to wavepower….

See also

www.el.angstrom.uu.se

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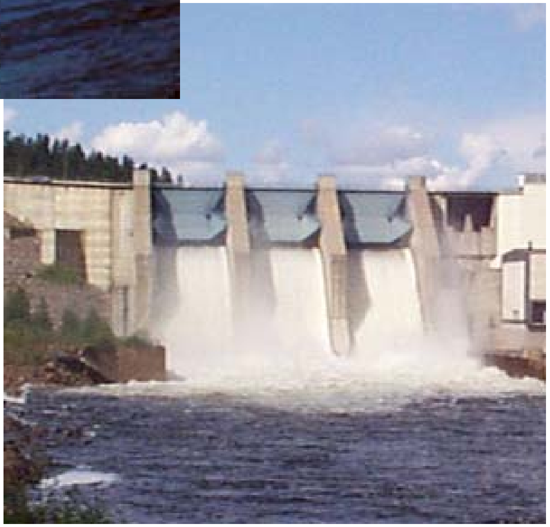
Wave power /energy



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$$P = k \cdot T \cdot h^2$$

$$P = U \cdot I$$

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Benefits with wave energy

- Large amounts of renewable, free energy
- Commercial potential more than the world's hydro power
- Relatively even energy flow over time – good complement to other energy systems

Issues:

Technology, Economy & Ecology

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Ocean waves:

...does not have a regular sinus shape!

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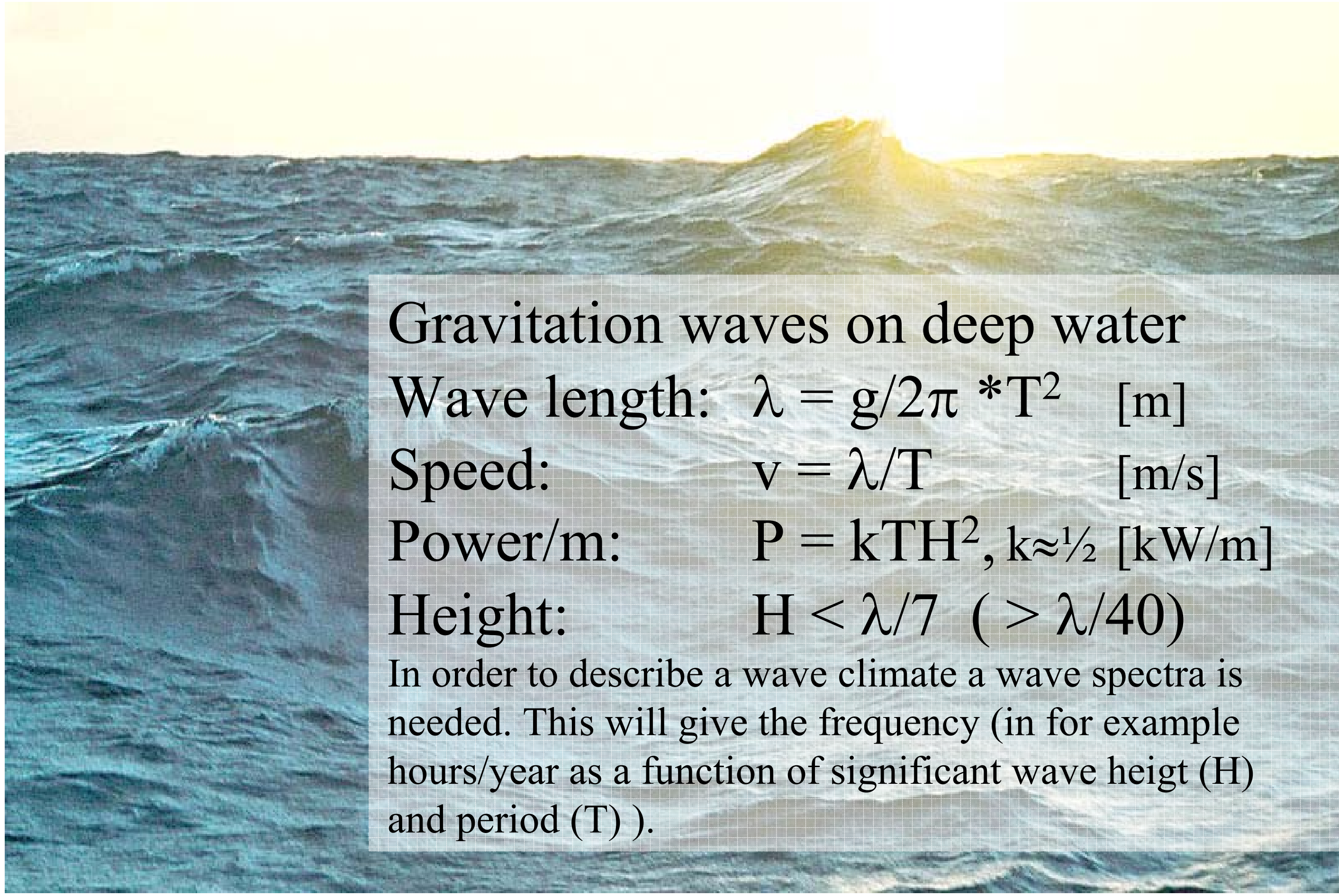
Ocean waves



Gravitation waves on deep water

Wave length: $\lambda = g/2\pi * T^2$ [m]

Speed: $v = \lambda/T$ [m/s]

Power/m: $P = kTH^2$, $k \approx ½$ [kW/m]

Height: $H < \lambda/7$ ($> \lambda/40$)

In order to describe a wave climate a wave spectra is needed. This will give the frequency (in for example hours/year as a function of significant wave heigt (H) and period (T)).

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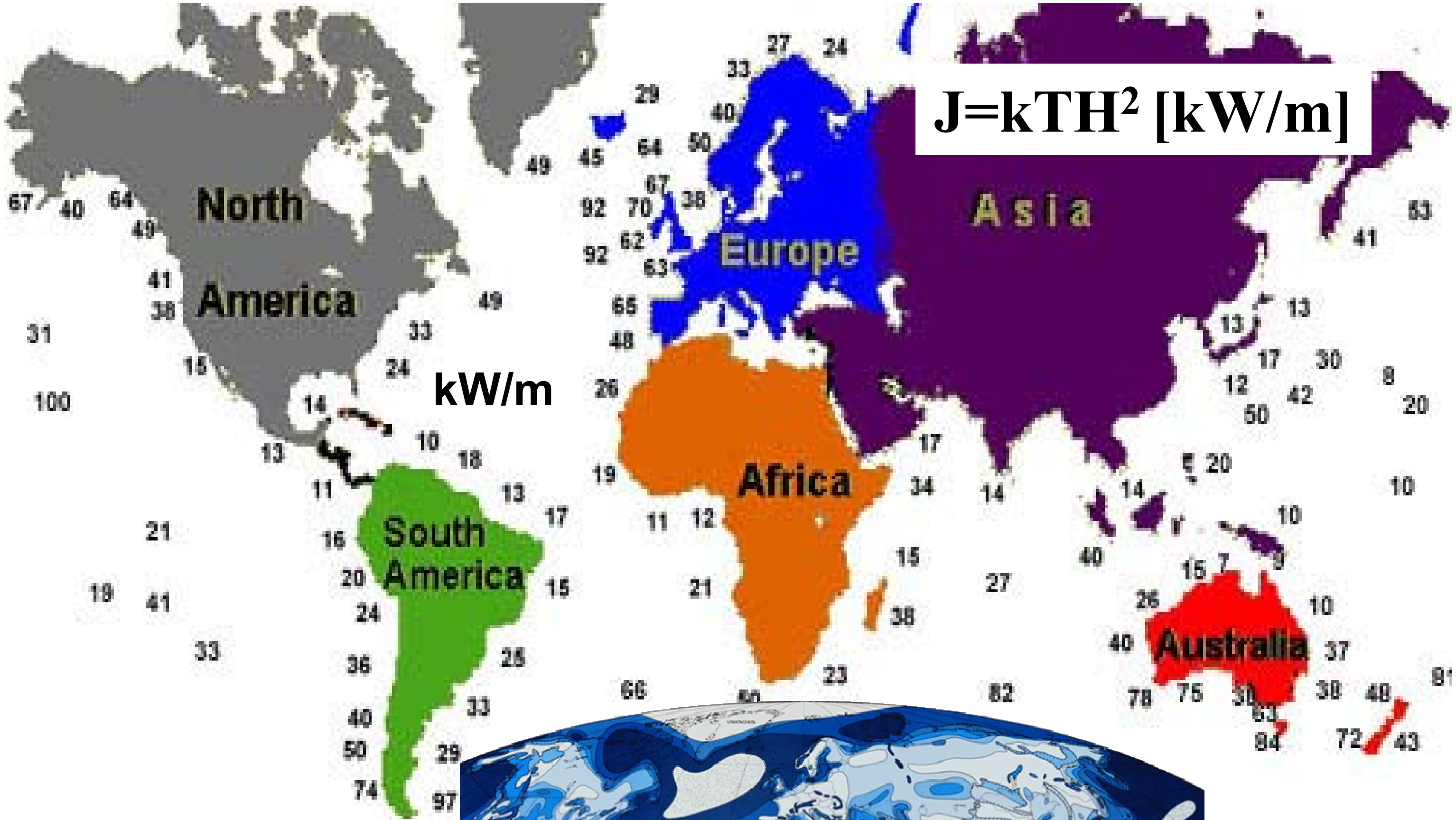
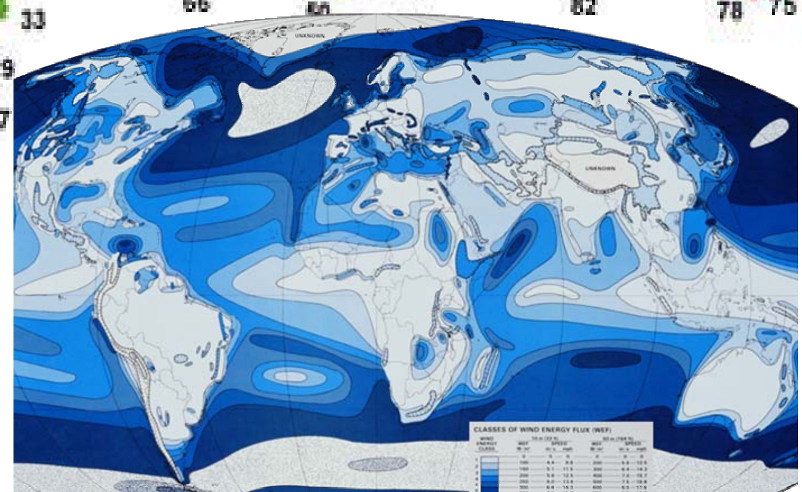
Power content

$$J = kTH^2 \text{ [kW/m]}$$





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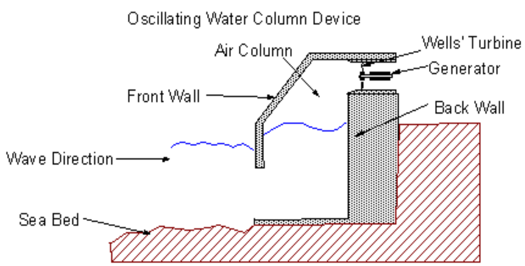
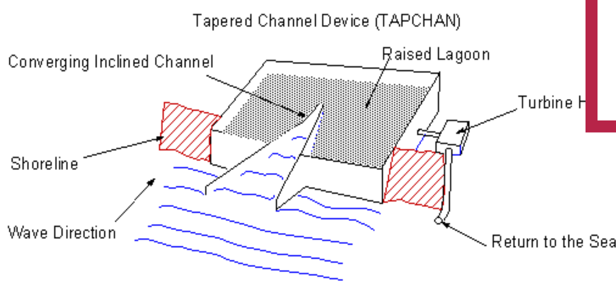
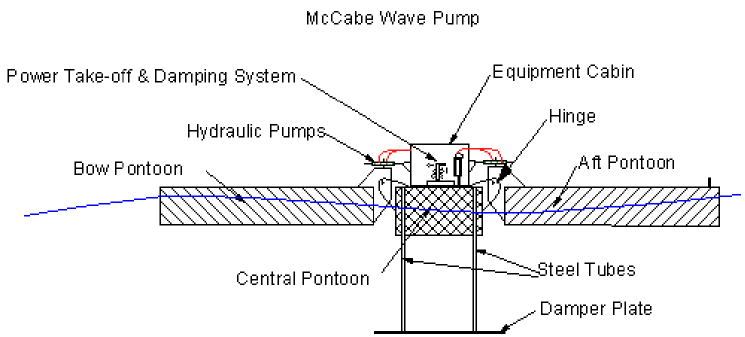
Today technology

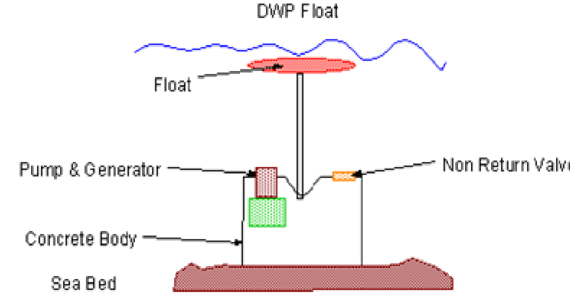
Diagram Shoreline Wave Energy Devices

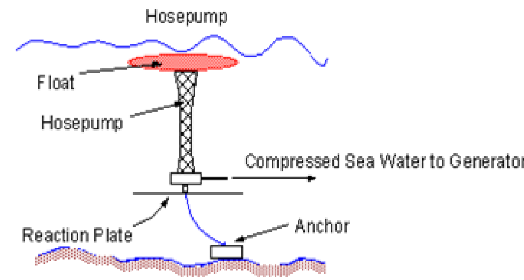


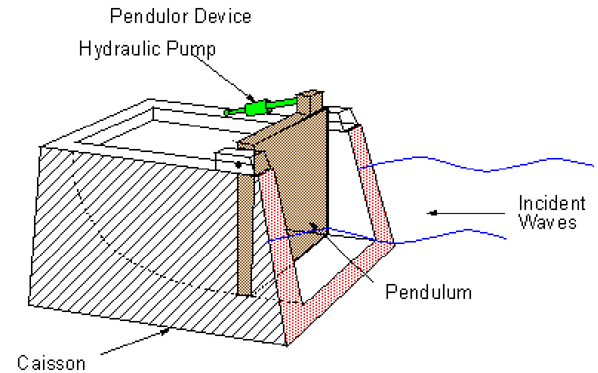




Wave motion have been adapted to std. generator







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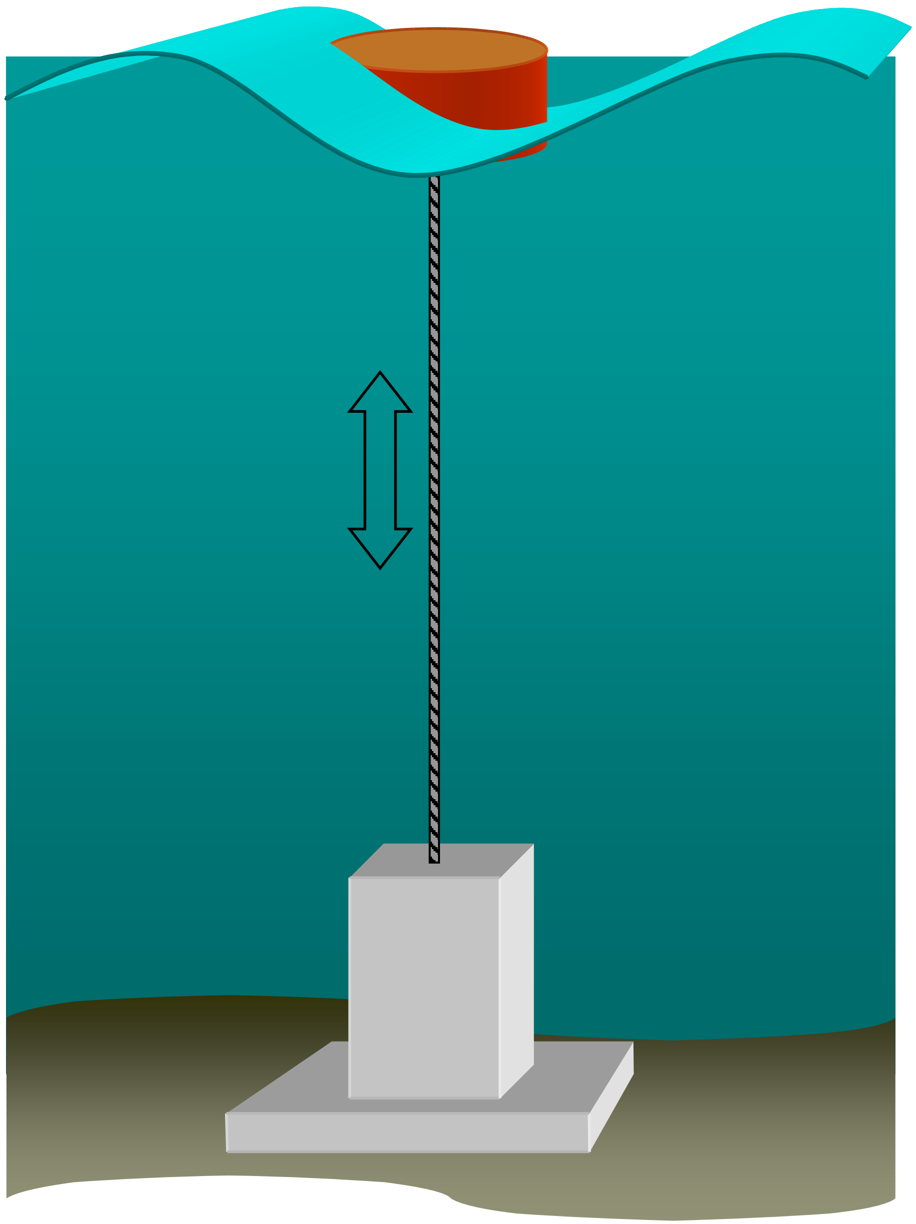

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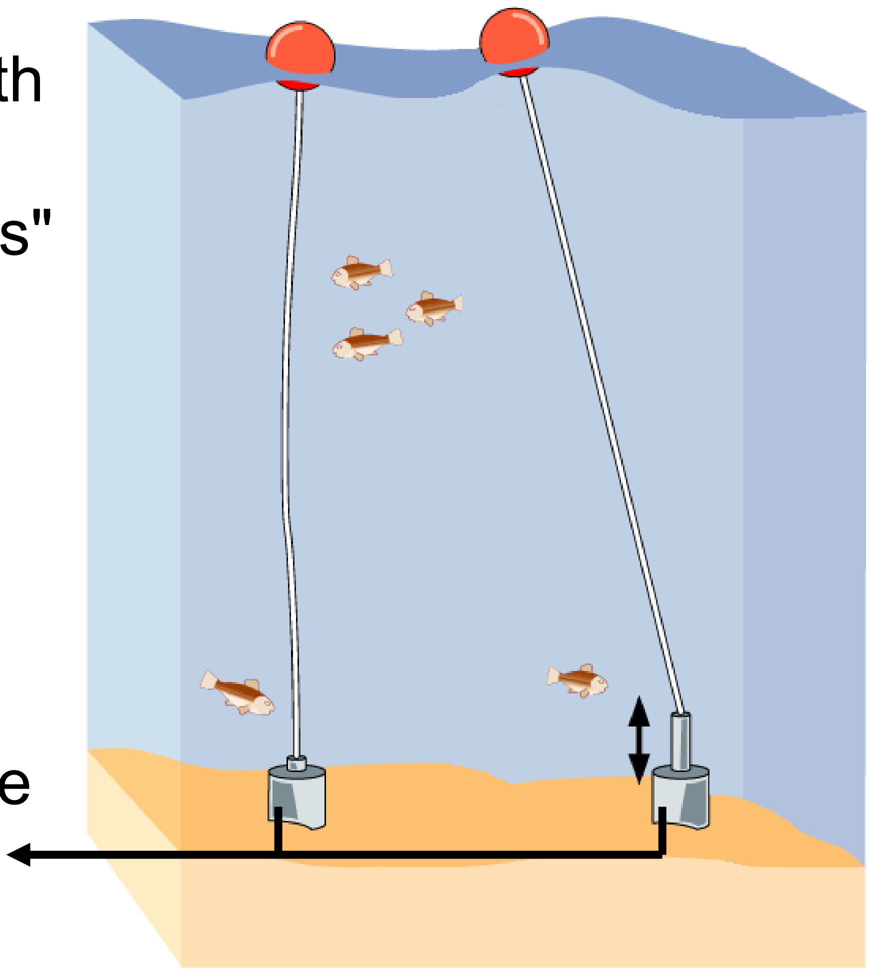
New technology

Adapt generator to the waves motion

Matrix with "Point Absorbers"



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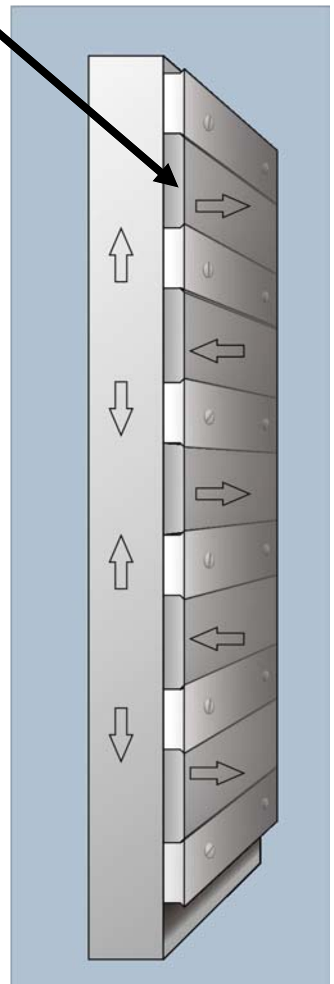
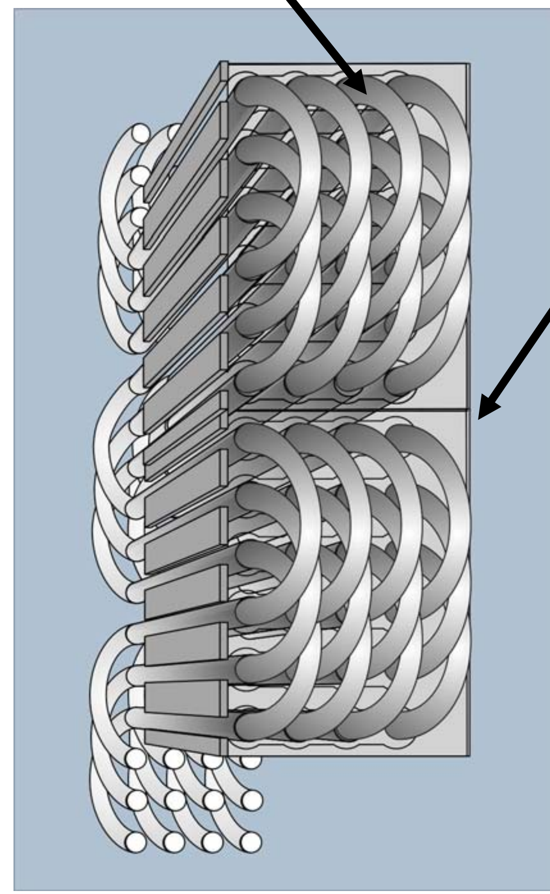
Linear generator

Neodymium-Iron-Bor-magnets



Three phase winding, standard cable



Elektro steel

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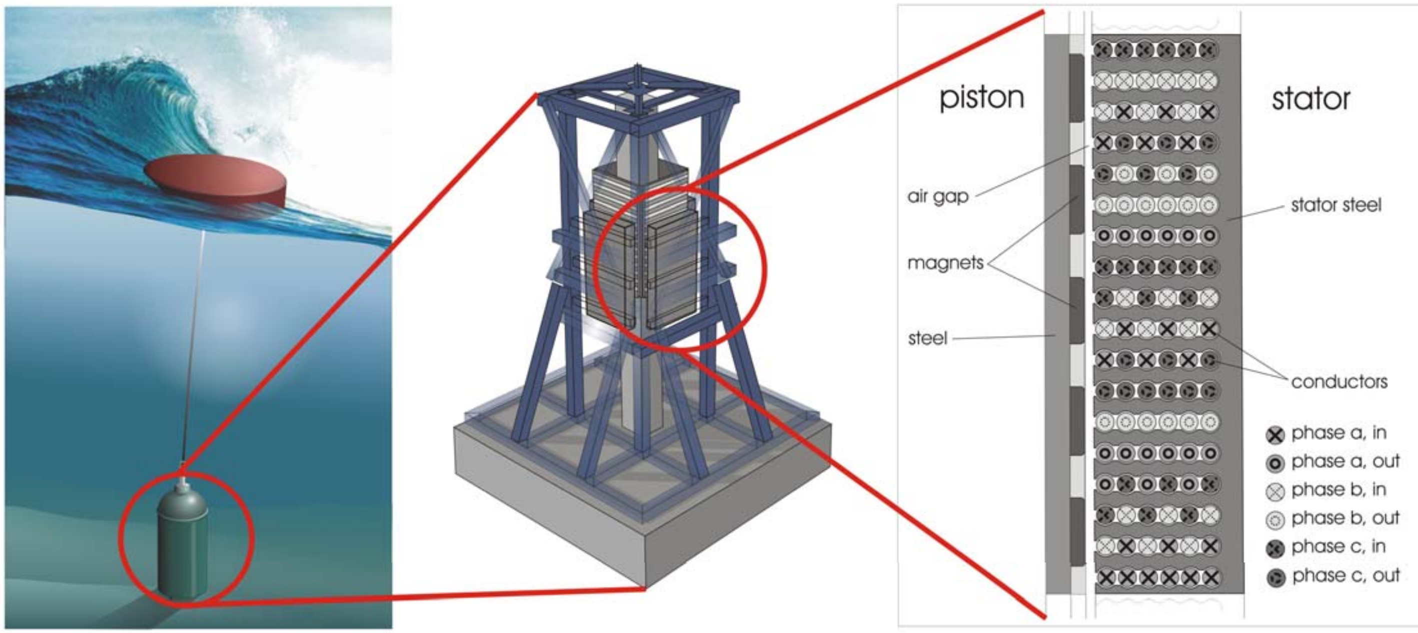
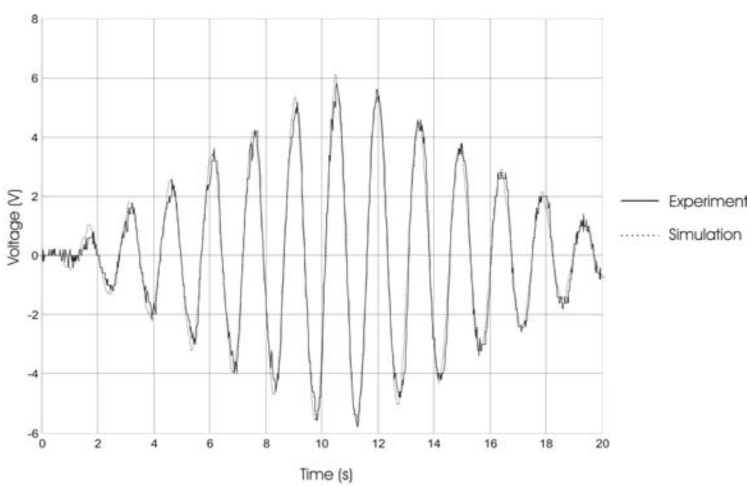
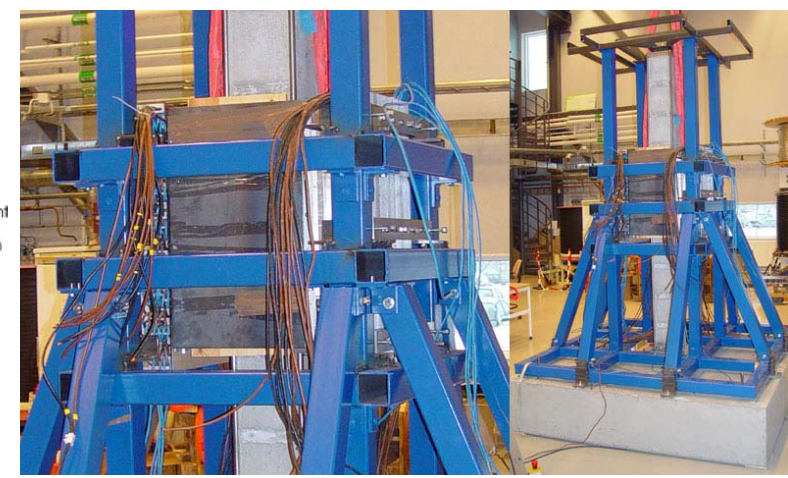
Linear generator







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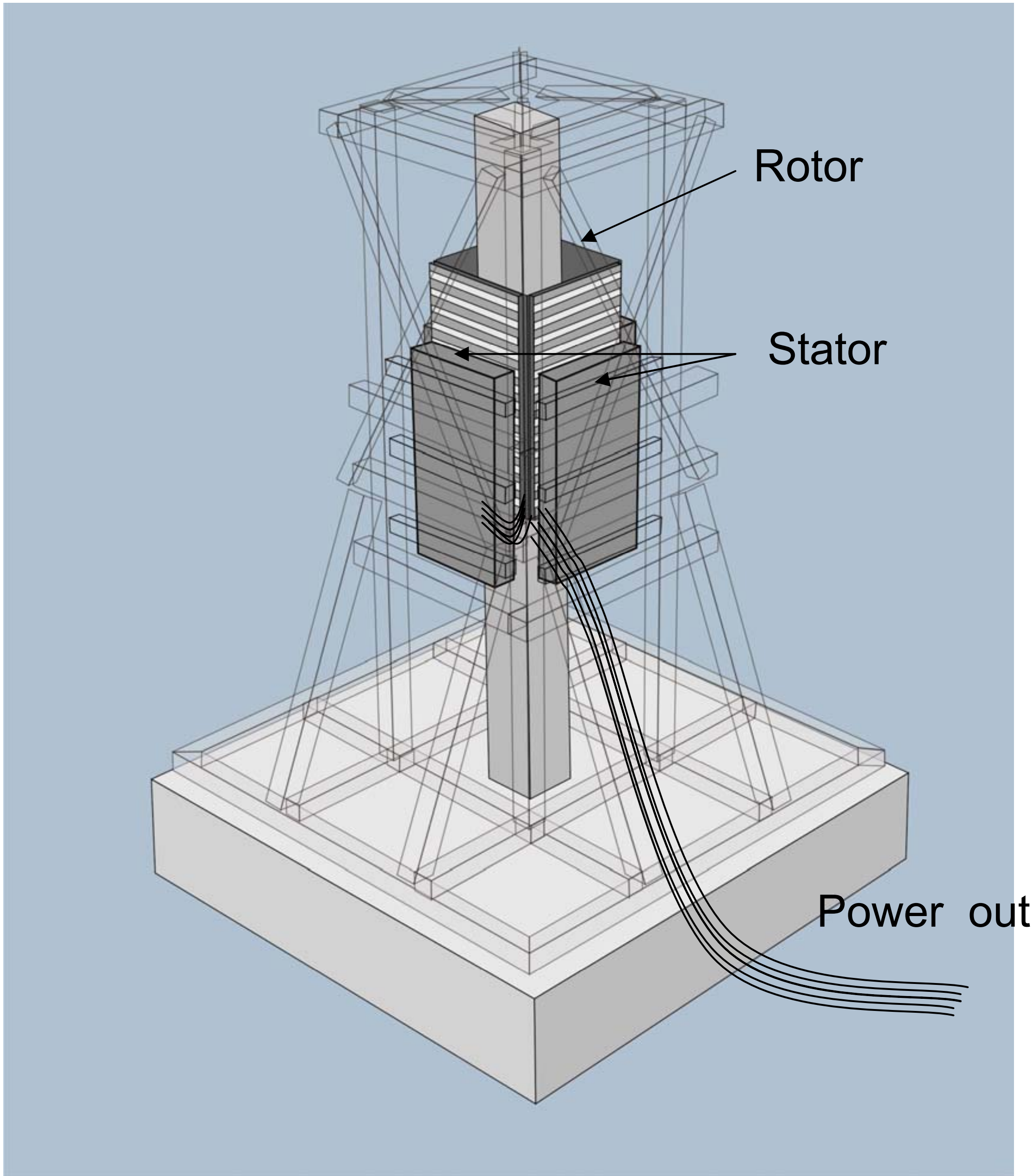
Design



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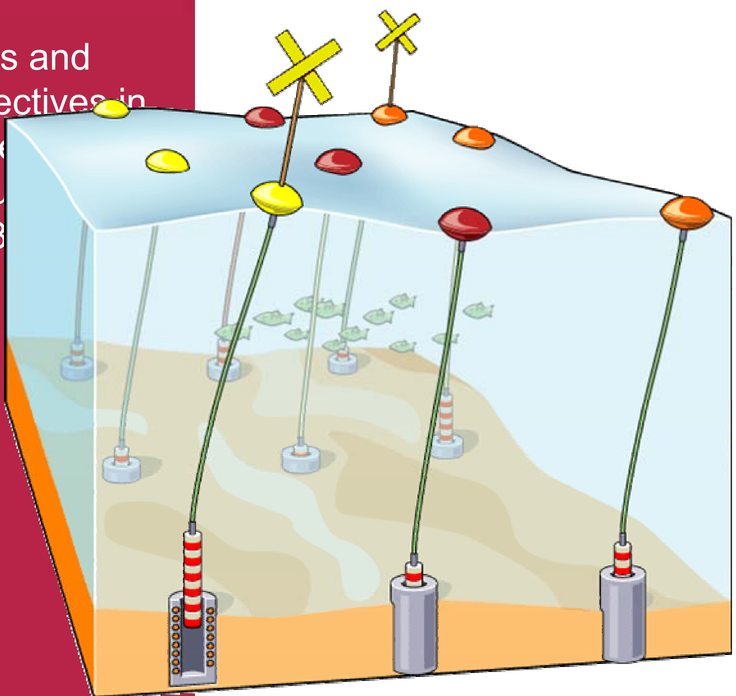
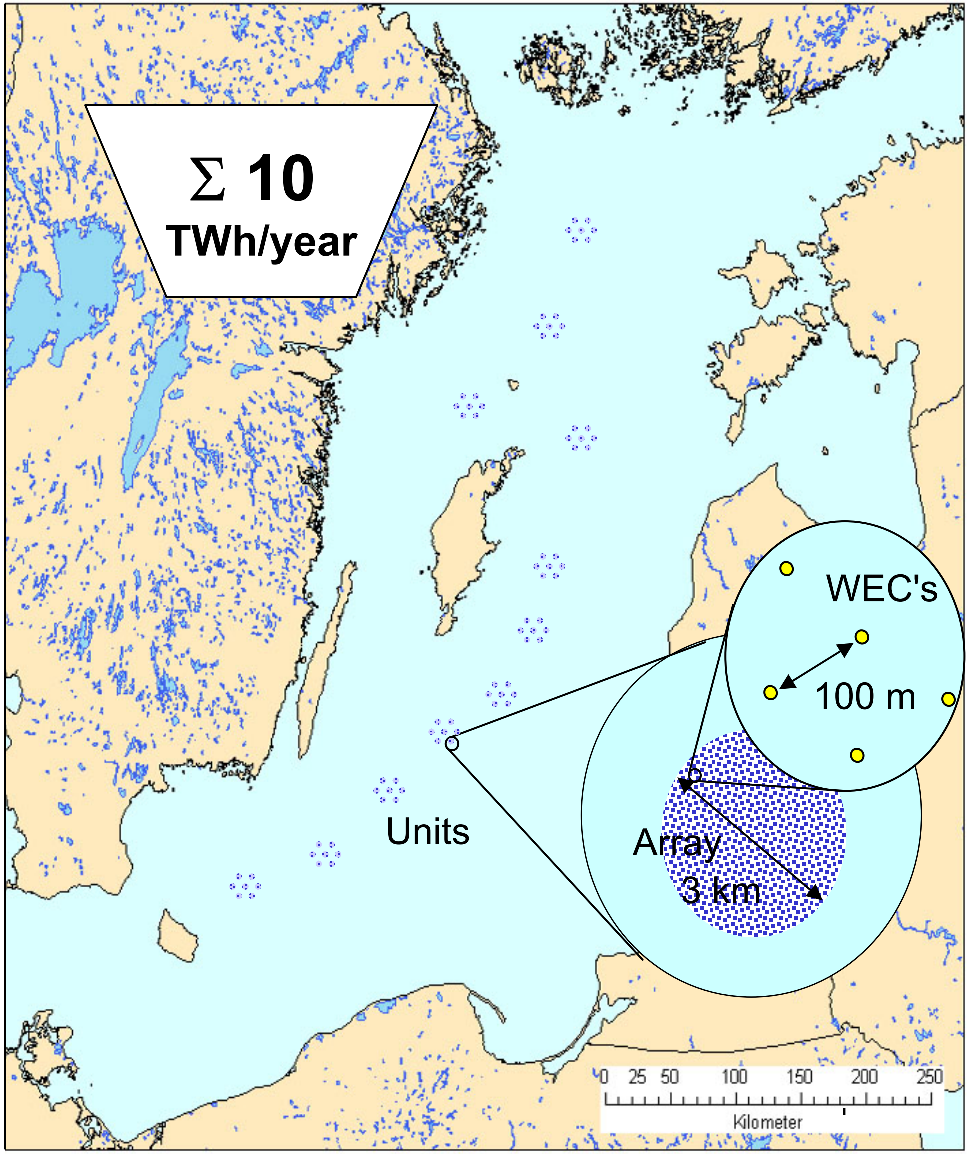
Deployment

Example: 10 kW systems deployed in 1 800 arrays





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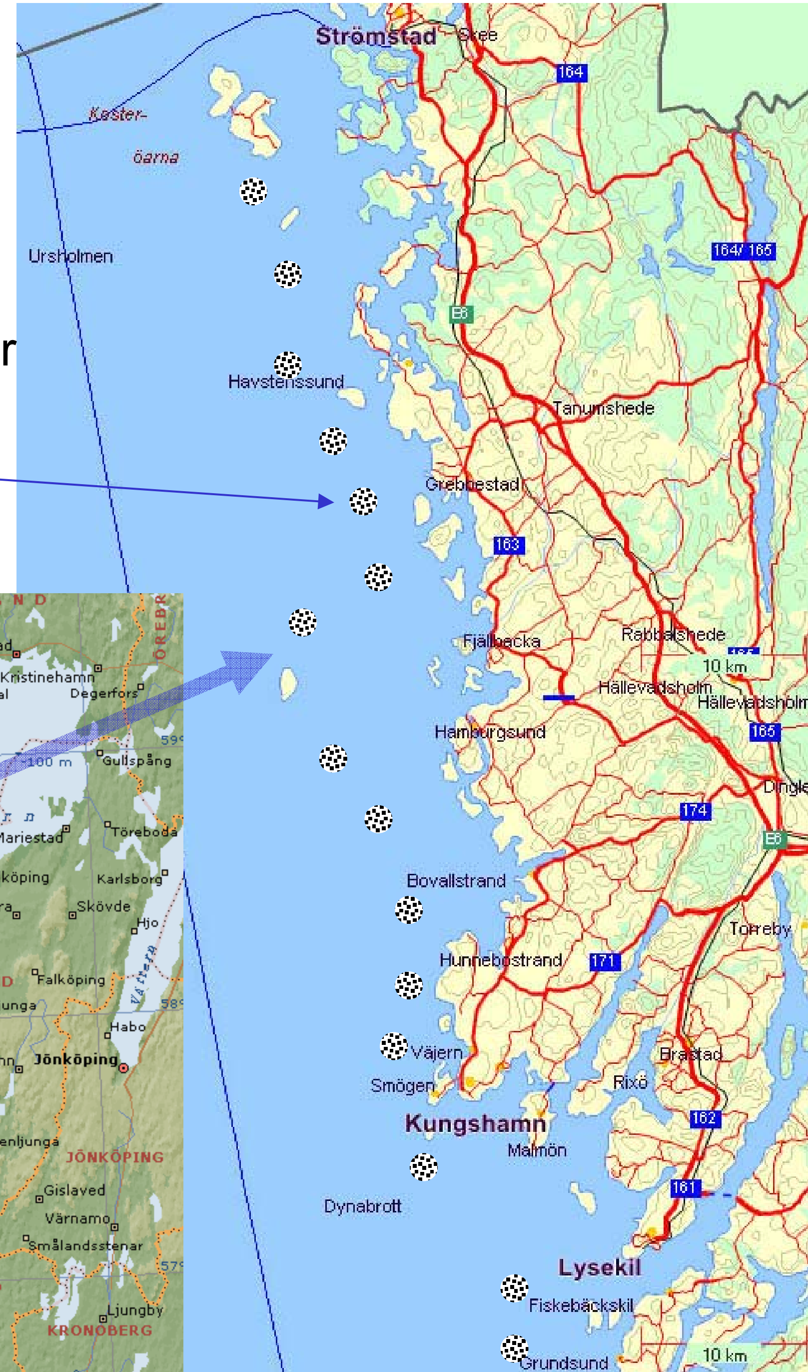
West coast area

- 10 MW (ca 40 GWh) Wavepower
- Totalt 1000 agg x 10 kW



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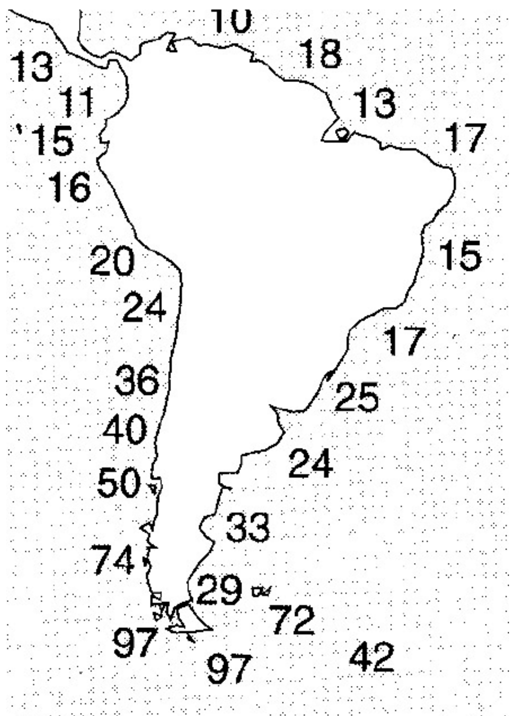
Resources



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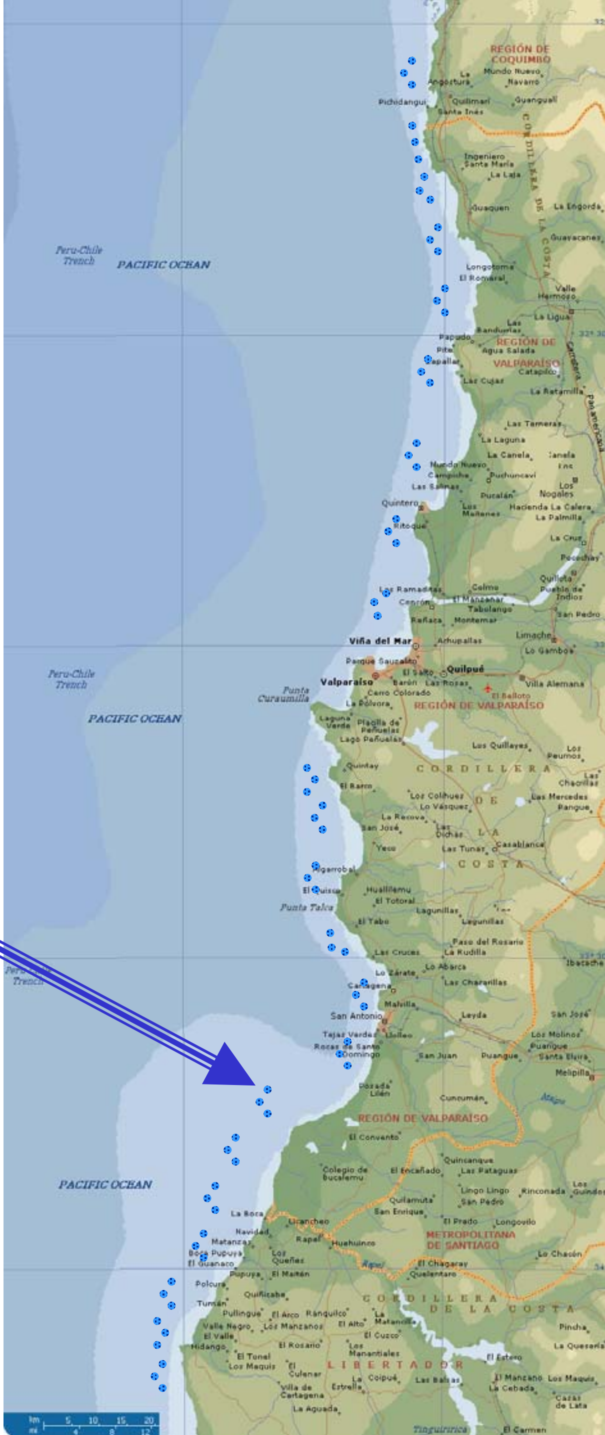
Case 10 TWh

- Chile today apprx. 40 TWh
- Interesting coast: 32° to 42° South
- This ex. 32° to 34°

Install 10 TWh
(correspongind to ½ of fossile fuel generation)

600 buoys (4m diam.) with 50 kW generator of 1.5 km diameter array
=> 30 MW or 0.15 TWh/year

i.e. **66 arrays => 10 TWh/year**



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”Lysekil project”

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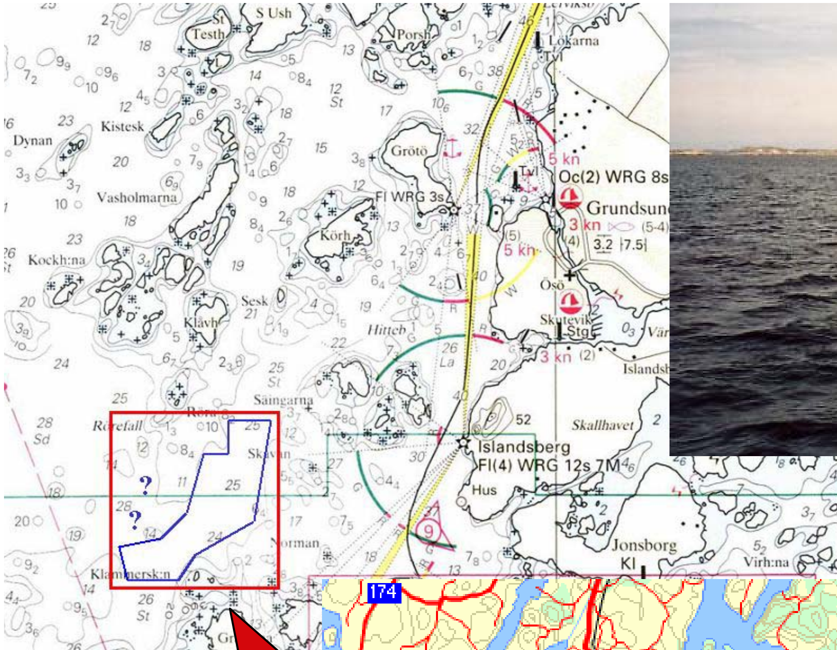
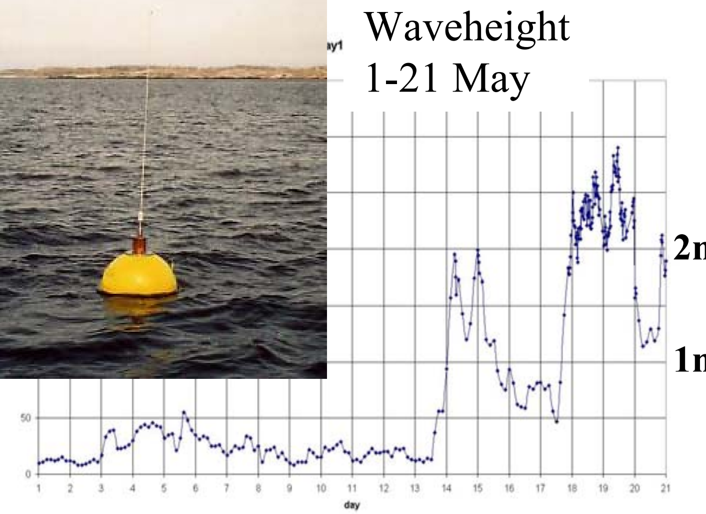
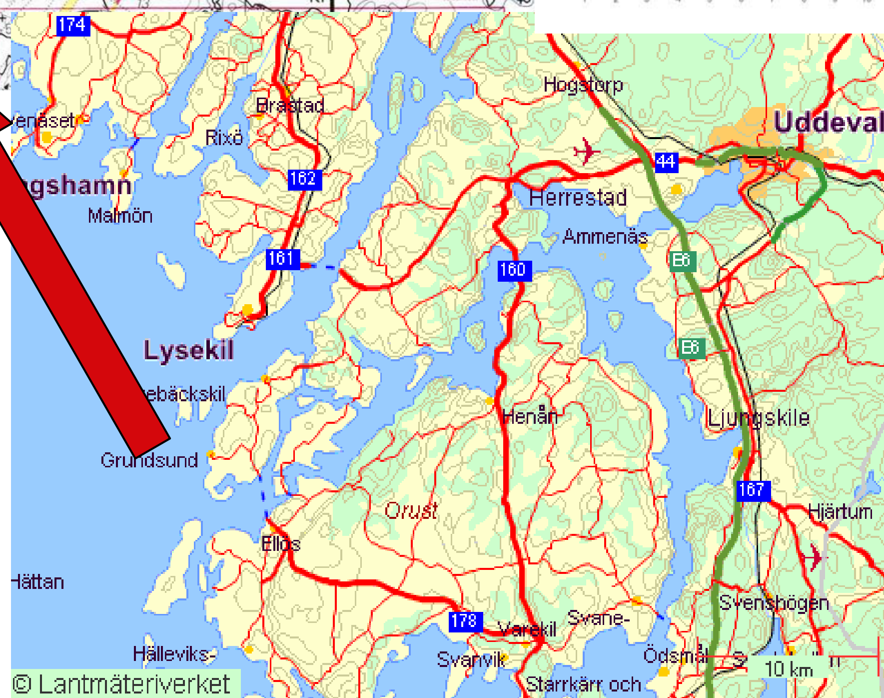
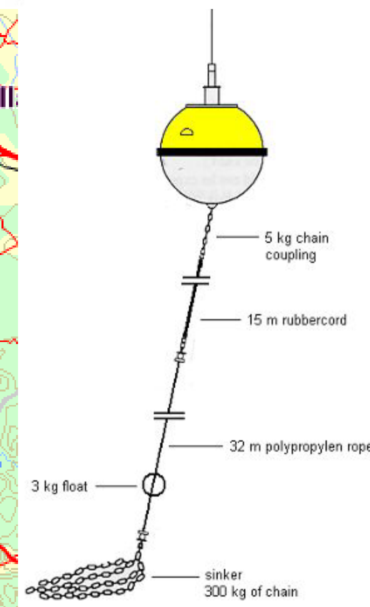
Lysekil, Islandsberg









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Now over to kinetic energy conversion….
Marine currents & Wind power

See also

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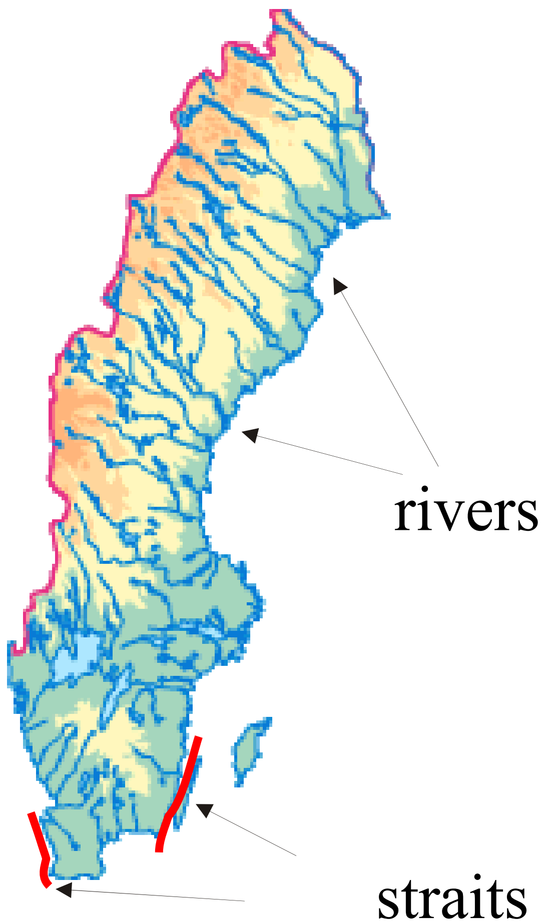
Background: Unregulated watercourses



- no tidal currents
- many rivers and some straits along the coast

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Question:

Is it possible to design a direct drive generator with good electromagnetic properties for the low turbine speeds and connect it to the AC grid?

Yes - but You can't read about it....

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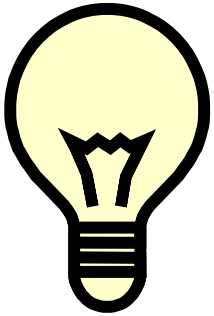
Maxwell's equations



$$\nabla \cdot \mathbf{D} = \rho_f \quad , \quad \nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$

$$\nabla \cdot \mathbf{B} = 0 \quad , \quad \nabla \times \mathbf{H} = \mathbf{j}_f + \frac{\partial \mathbf{D}}{\partial t}$$

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Theory

$$\boldsymbol{H}\cdot(\nabla\times\boldsymbol{E})=\nabla\cdot(\boldsymbol{E}\times\boldsymbol{H})+\boldsymbol{E}\cdot(\nabla\times\boldsymbol{H})$$

$$\boldsymbol{H}\cdot\left(-\frac{\partial\boldsymbol{B}}{\partial t}\right)=\nabla\cdot(\boldsymbol{E}\times\boldsymbol{H})+\boldsymbol{E}\cdot\left(\boldsymbol{j}+\frac{\partial\boldsymbol{D}}{\partial t}\right)$$

$$\boldsymbol{E}\cdot\left(\frac{\partial\boldsymbol{D}}{\partial t}\right)=\frac{\partial\left(\boldsymbol{\varepsilon}\boldsymbol{E}^2/2\right)}{\partial t}$$

$$\boldsymbol{H}\cdot\left(\frac{\partial\boldsymbol{B}}{\partial t}\right)=\frac{\partial\left(\boldsymbol{B}^2/2\mu\right)}{\partial t}$$

Gauss

$$\oint_S(\boldsymbol{E}\times\boldsymbol{H})\cdot d\boldsymbol{a}+\int_V\boldsymbol{j}\cdot\boldsymbol{E}\,d\tau=-\frac{\partial}{\partial t}\int_V\left(\frac{\boldsymbol{\varepsilon}\boldsymbol{E}^2}{2}+\frac{\boldsymbol{B}^2}{2\mu}\right)d\tau$$

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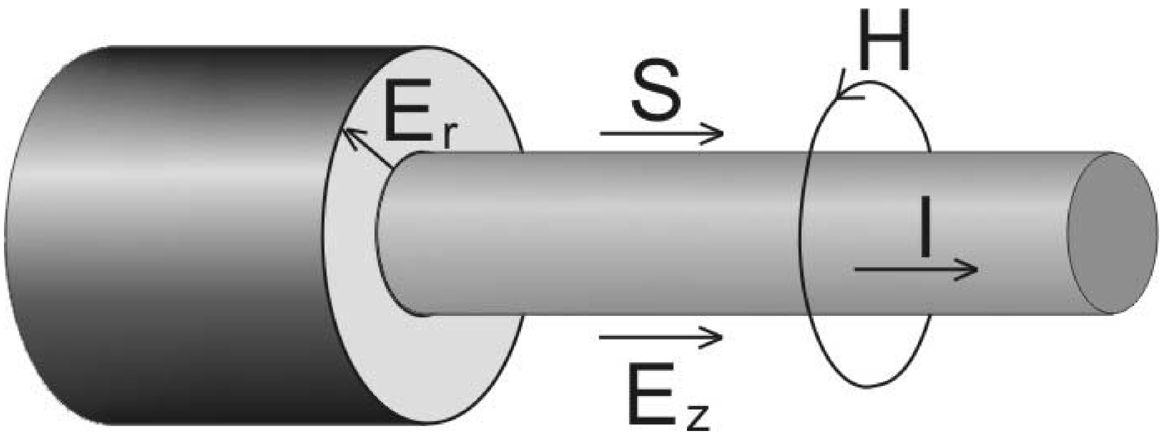
Poyntings vector

$$\boldsymbol{S} = \boldsymbol{E} \times \boldsymbol{H}$$



Direction of fields and vector components in a conductor.

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Design parameters

	E kV/mm	I A/mm^2	Power density kVA/mm^3
Traditional	2 - 3	3.5 - 4.5	7 – 13.5
High voltage	10 - 15	1.5 - 3	15 - 45

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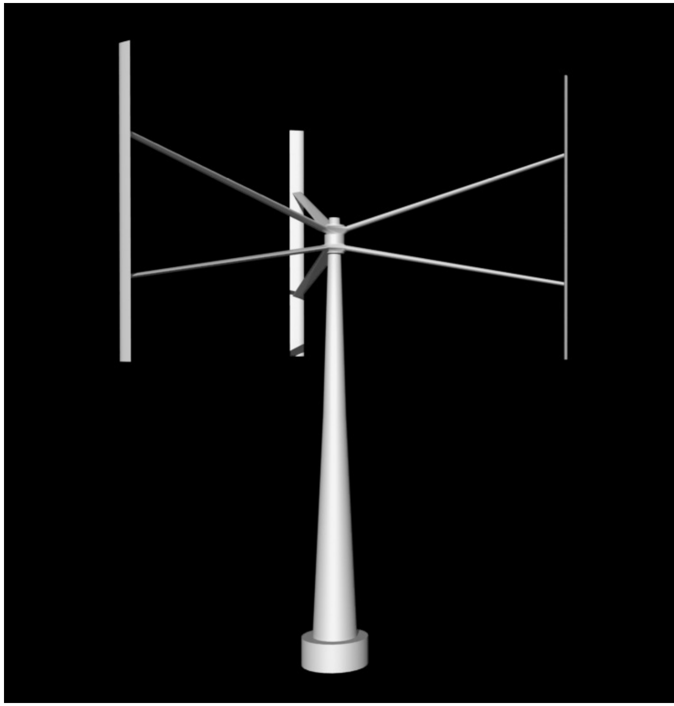
Background: Vertical Axis Turbines



- •generator on ground
- •rotationally symmetric/independent of flow direction
- •both the turbine radius and height can be changed
- •no blade regulation
- •start winding

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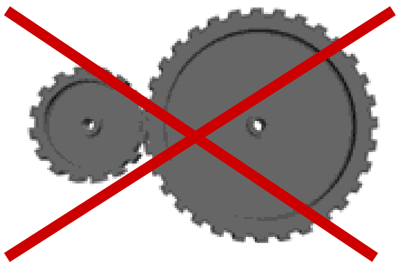
Background: Direct Drive System



- overloads are handled electrically
- no transformation of momentum
- higher working efficiency
- less maintenance
- less environmental impact
- results in low generator speed

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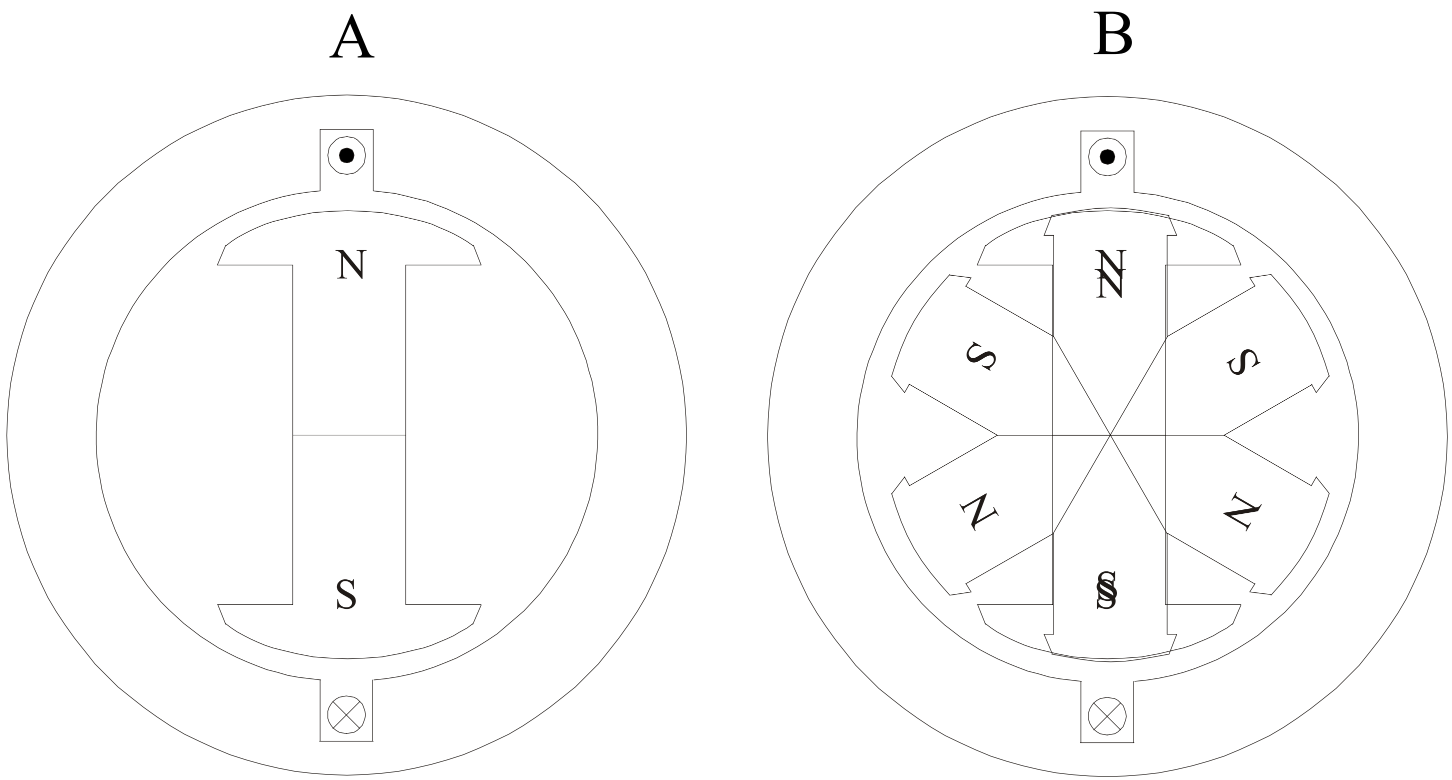
One way to compensate for the low speed:



$$\frac{d\Phi_A}{dt} \ngeq \frac{d\Phi_B}{dt}$$

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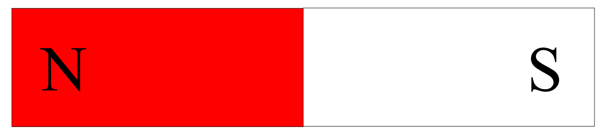
Background: Permanent magnets



- Simple construction
- No transitions between rotor and stator, for example carbon brushes, needed
- No rotor current losses
  - Can be large for multipole machines
- Reduced need for maintenance
- Material
  - Fe
  - NdFeB

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Simulations:

Example:

20kVA generators with varying rotation speed

The same base configurations

Varying parameters:

- Rotation speed (19 - 47 rpm)
- Number of poles (46 - 114)
- Diameter (1.0 - 2.5 m)

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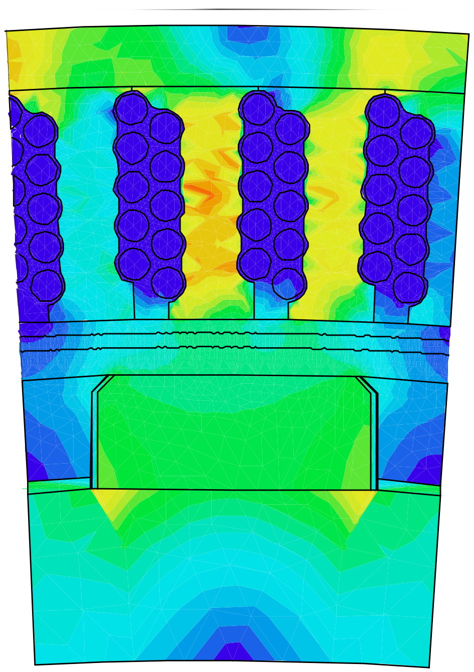
Simulations: Basic steps

- Define a geometry
- Assign material properties
- Solve electromagnetic field equations and thermal equations
- Steady state and time dependent solutions



Cross section of one pole

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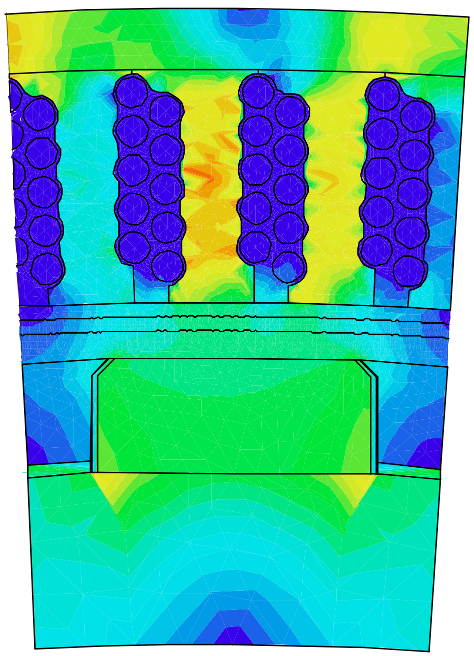
Simulations: Result parameters

- Induced voltage, currents
- Load angle
- Iron losses
- Resistive losses
- Length



Cross section of one pole

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In reality…

- Large diameter low speed PM generator

Patentansökan från Swedish Vertical Wind AB

Elektrisk anordning och förfarande
Sökt patent: SE200064 A
Publiceringsdatum: 2003-07-11
Uppfinnare: LEIJON MATS; BERNHOFF HANS
Sökande: SWEDISH VERTICAL WIND AB (SE)
Ansökningsnummer: SE20020000064D 20020110
Prioritetsnummer: SE20020000064 20020110
IPC klassning: F03D3/00
Offentliggjort dokument: Inget dokument tillgängligt

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First Turbin Tests

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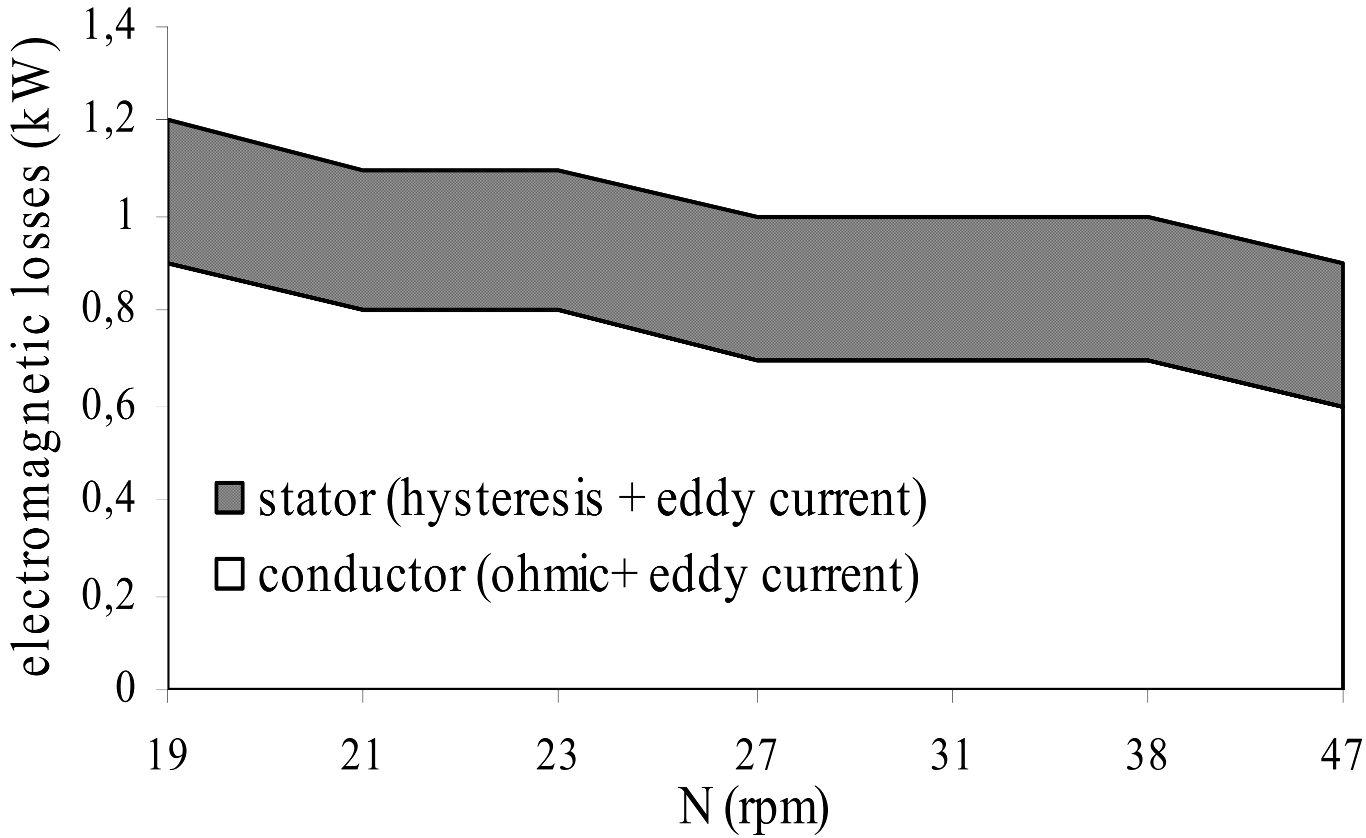
Results:
Electromagnetic power losses (kW)



Electromagnetic efficiency: 94% - 95.5%

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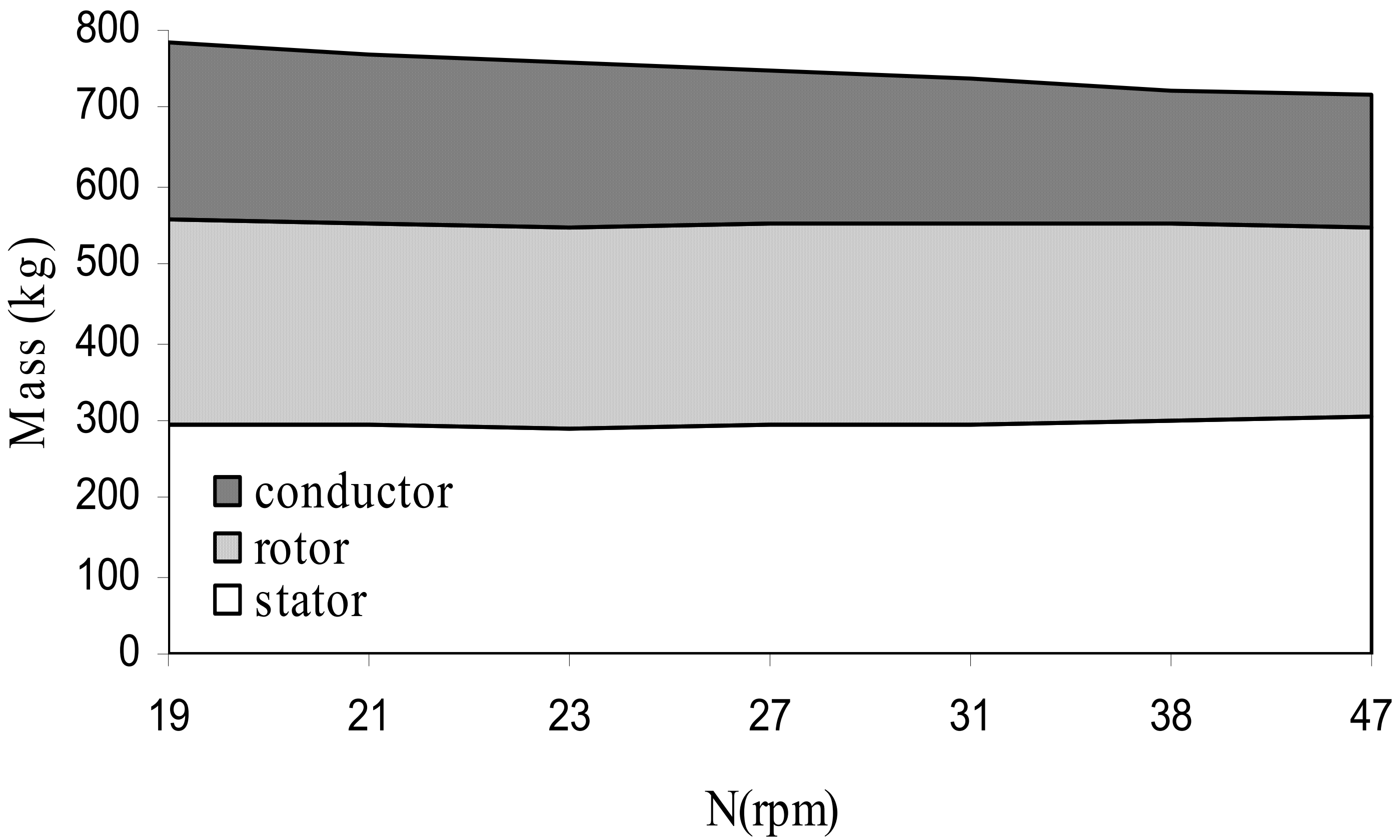
Results:
Material weights (kg)



Total material weight: 780 - 715 kg

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Demand Grid Connection

50/60 Hz Grid

Power (reactive and active) acceptance

Low losses

Low maintenance

Simple arrangement

Protection

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Base unit

Single line diagram for base unit

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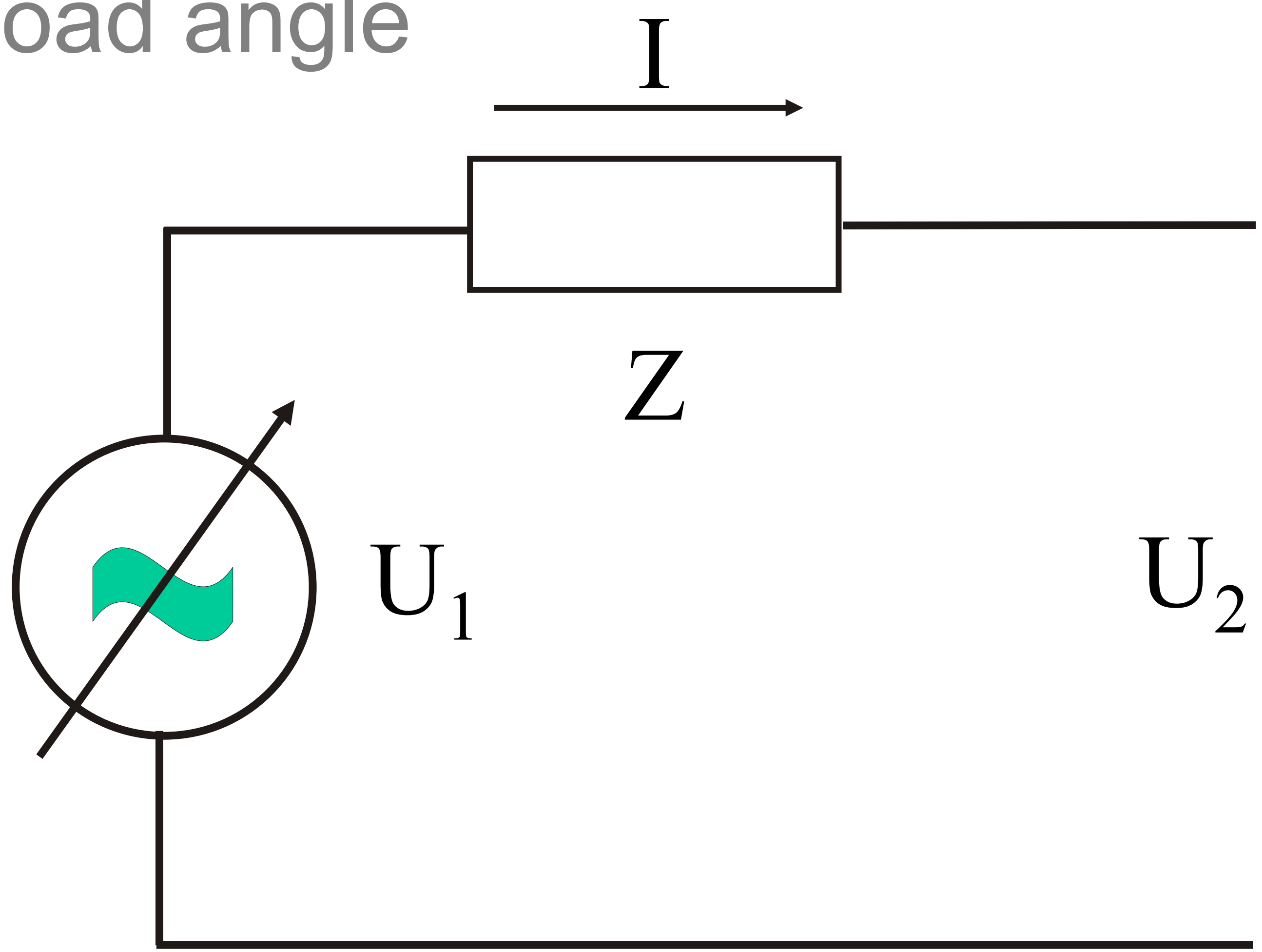
Load angle



Phase angle between noload and load

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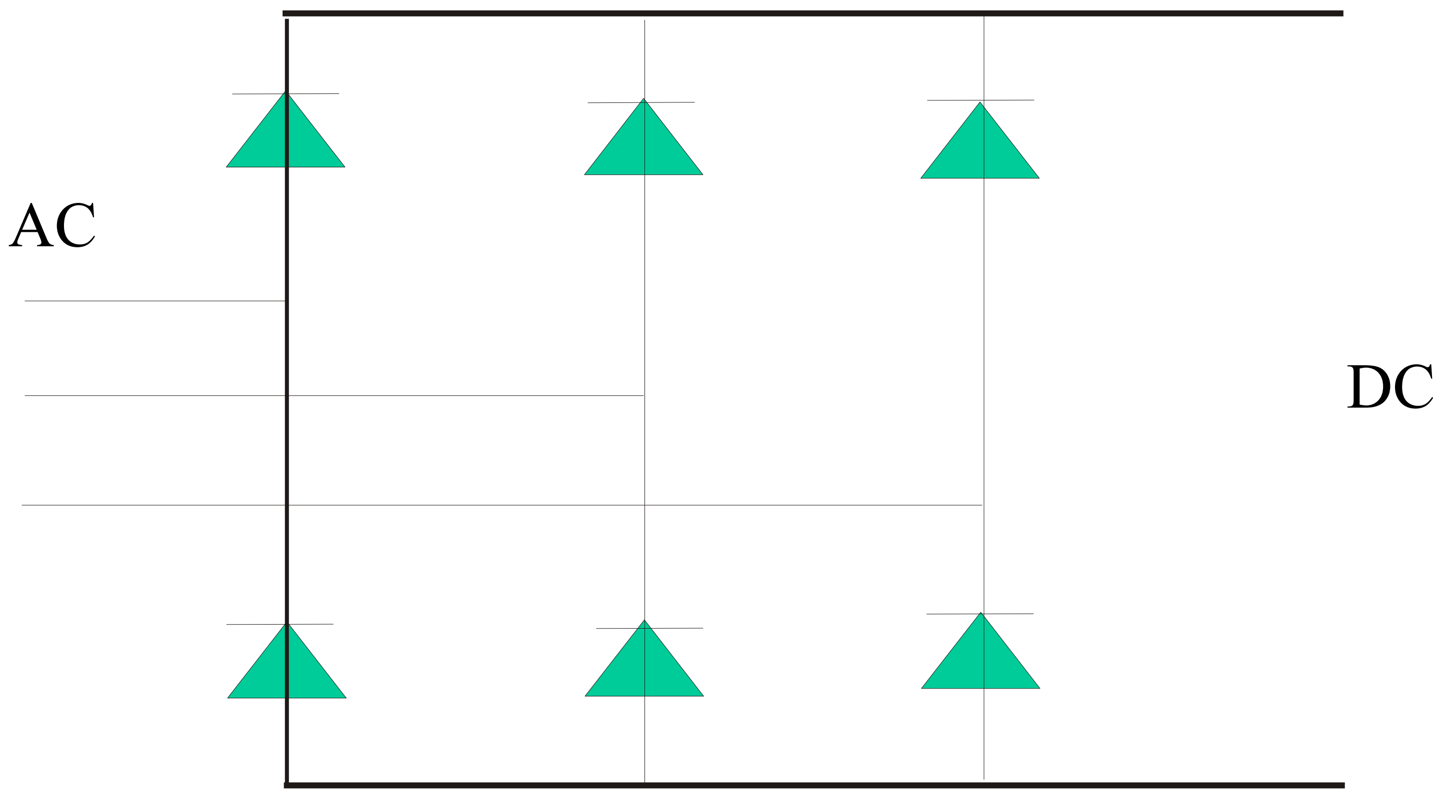
Diode Rectifier



Low load angle gives possibility to use simple, low loss and low cost diodes

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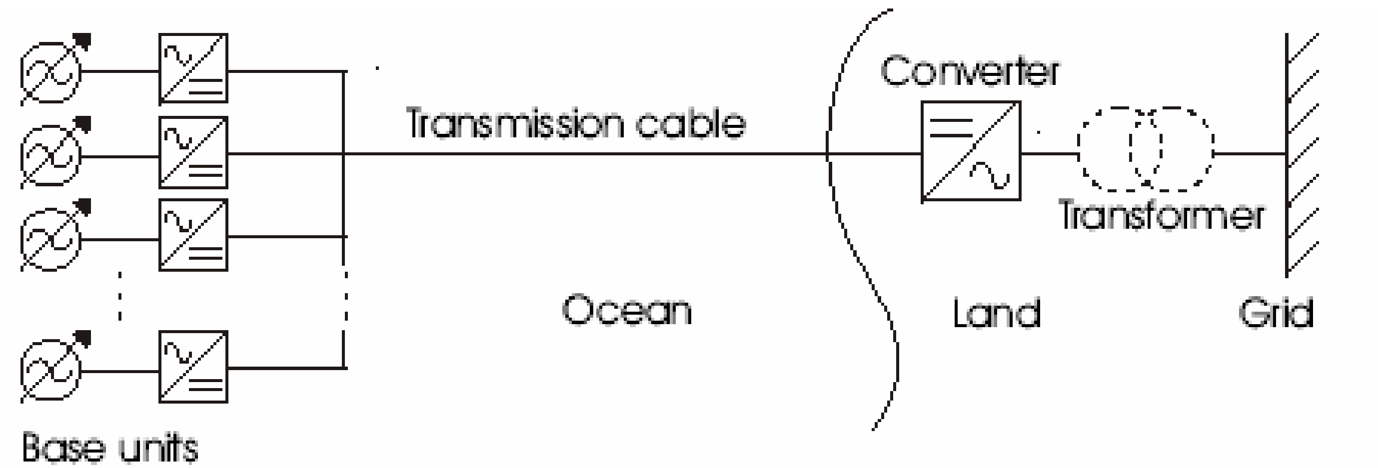
DC transmission



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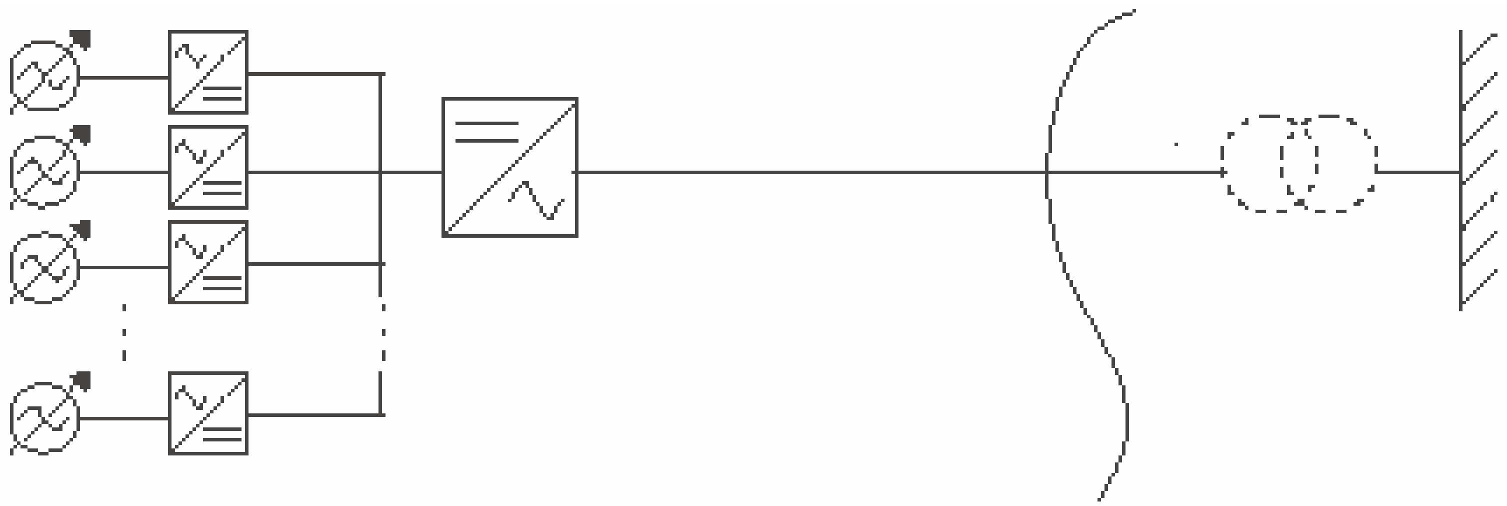
AC transmission



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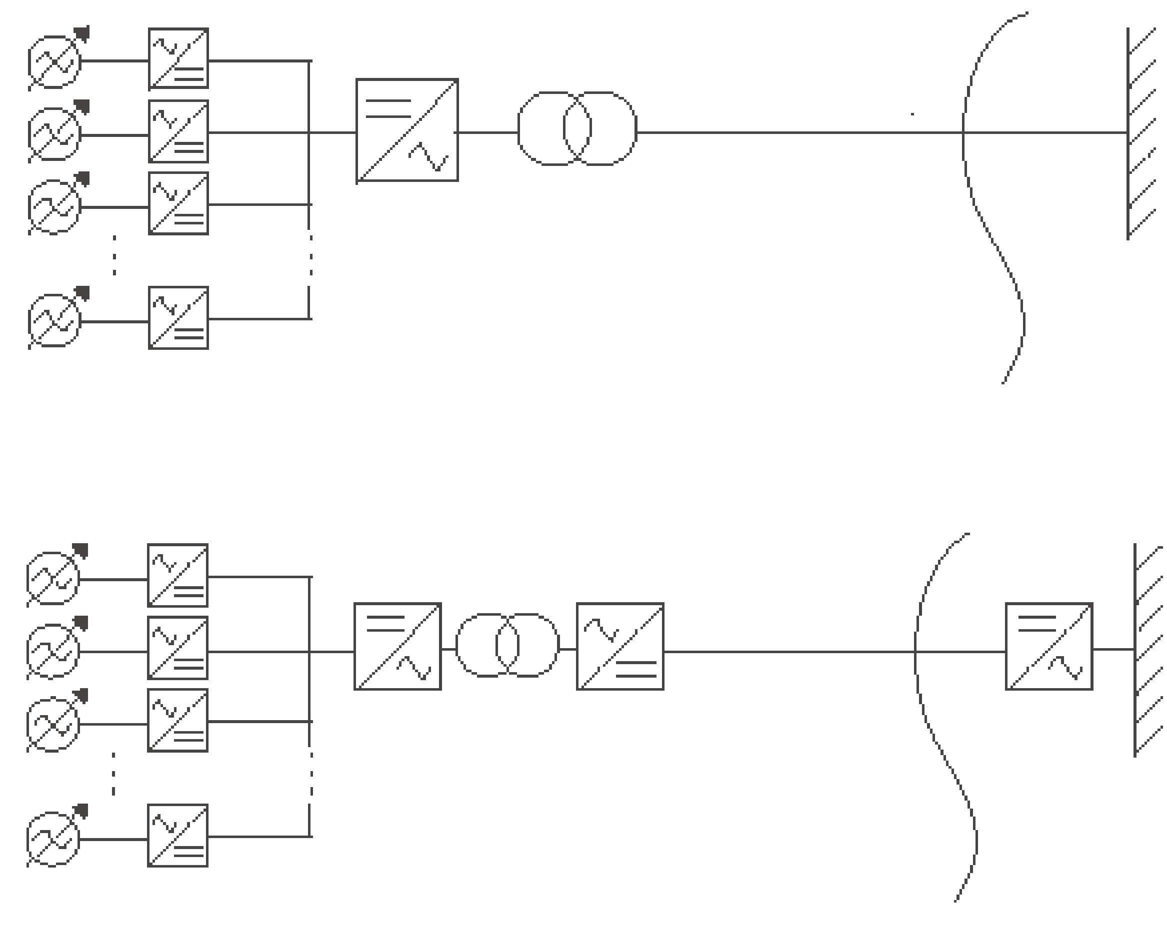
Possibilities – higher voltages



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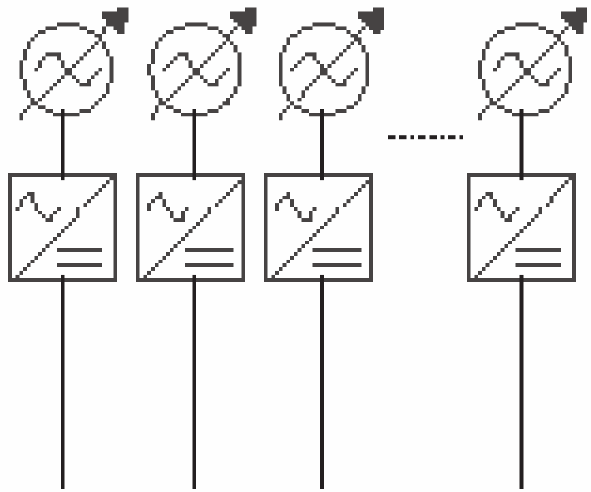
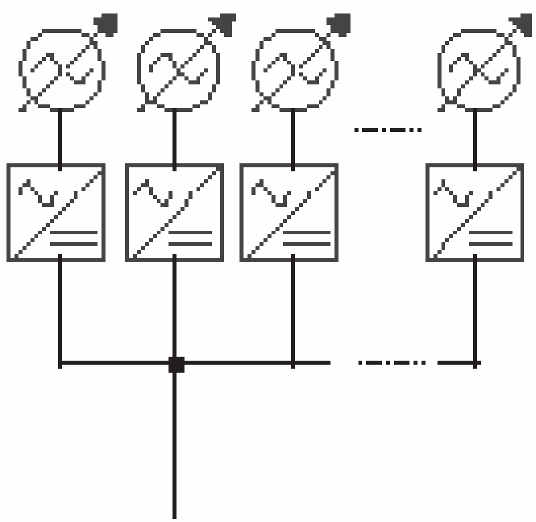
Reliability



High

Low



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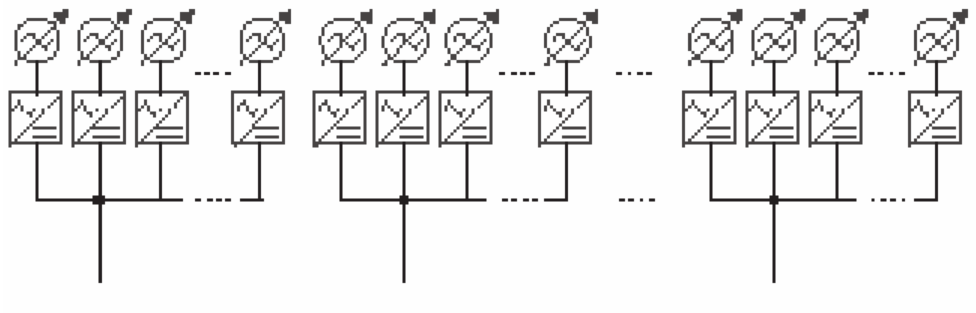
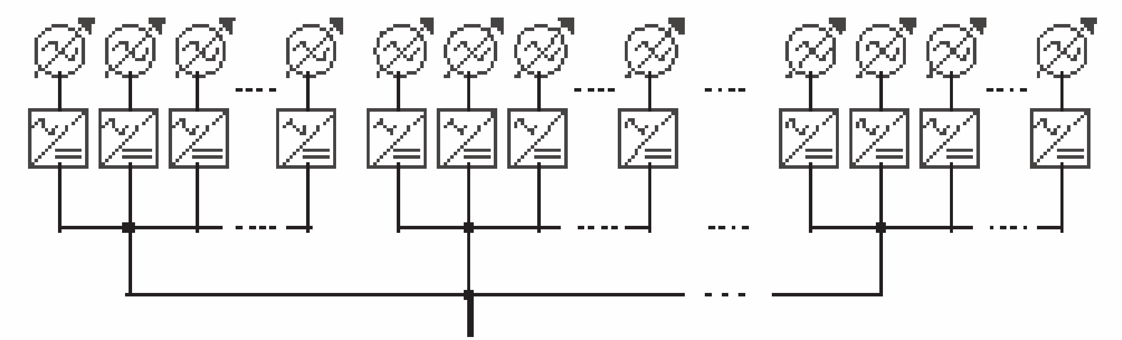
Combinations



Cost/losses versus reliability….



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Conclusion:

It is possible to design direct drive generator with an electromagnetic efficiency of at least 94% and connect it to grid.

Now, You know how...

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Thank You for Your attention

for further information and progress in the project please note

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