Multiphysics Challenges for Renewable Energy Devices

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Høgskolen i Narvik

Renewable Energy

In recent years environmental issues due to man’s activities have come into focus. One of the major concerns has been the present use of various types of fuels that are finite resources and which through chemical reactions give rise to gases which may have an harmful effect on our environment. Consequently, there has been a move towards developing technology that do not use fossil fuel or any other fuel of limited resource. It is suggested that oil production will reach a peak in 2016.

‘Renewable Energy’ has taken on the meaning of all energy that is obtainable without using fossil fuel or any other fuel of limited resource

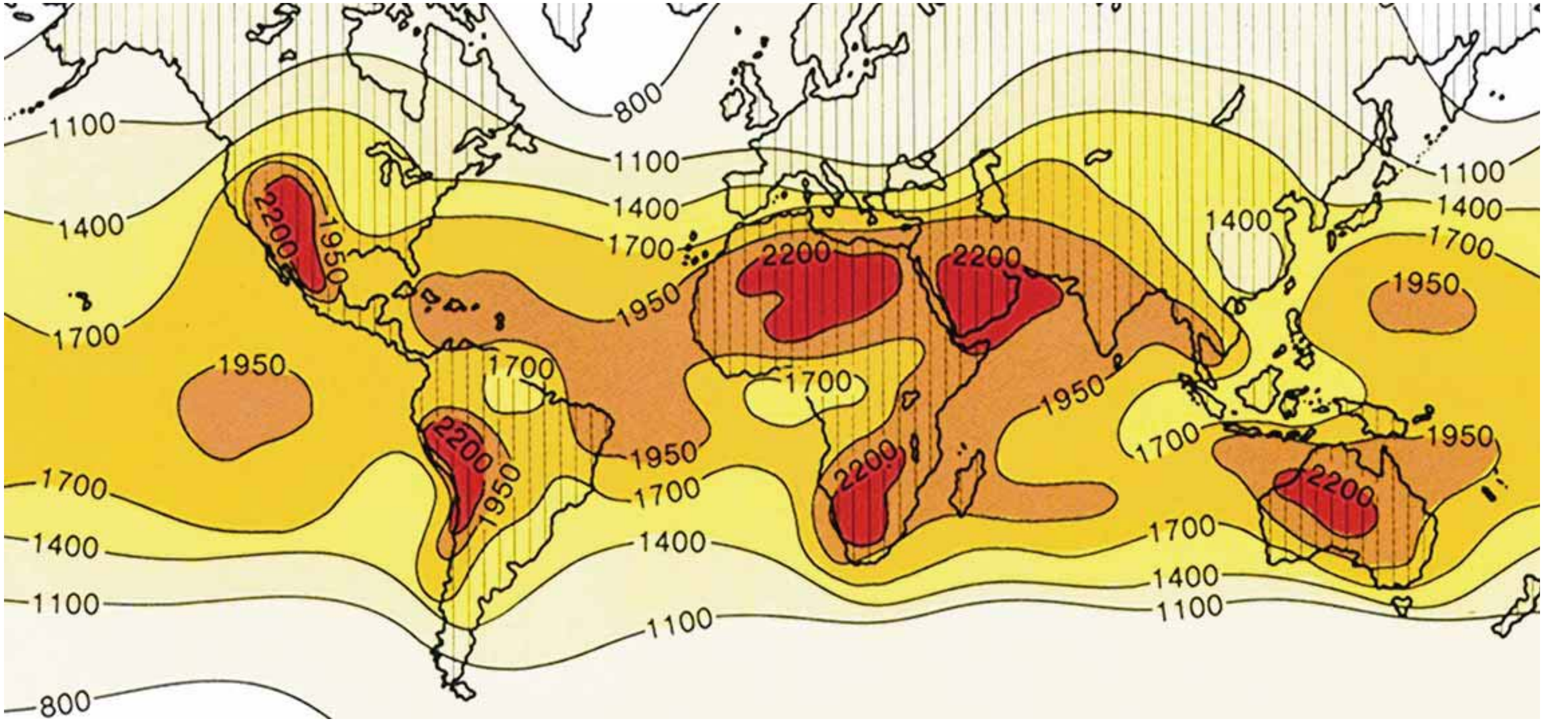
Energy Sources

There are many natural energy sources available to us. It is the utilisation of these sources which needs attention and technological development. It is known that production of oil may reach its peak in the next decade.

- SOLAR ENERGY
- WIND ENERGY
- WAVE ENERGY
- TIDAL ENERGY
- GEOTHERMAL ENERGY
- HYDRO ENERGY
- OCEAN THERMAL ENERGY
- BIOENERGY
- SALT GRADIENTS / OSMOTIC PRESSURE

Solar Energy

in kWh/m2 on a horizontal surface for world



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Example of Solar Energy

The annual solar energy reaching the surface of **Norway** (region of comparative low potential) equals **1700 times** the annual national energy demand. The annual radiation varies from approximately 700 kWh/m2 in the north to over 1100 kWh/m2 in the south. Moreover, the variations over the year are large, a cloudless day in June in southern Norway giving 8.5 kWh/m2, while an overcast winter day may only yield 0.02 kWh/m2.

Of course beyond the arctic circle the sun does not rise above the horizon at present.

Never the less good solar energy technology could give Norway all its energy needs

Potential of other Energy Sources

The wind is driven by solar energy, and the processes responsible for this absorb approximately 1% of the solar energy reaching the earth. For the entire earth this amounts to 100 times the world's energy consumption.

Ocean waves transport energy over large distances, from storm centres in the oceans to distant shores. The waves beating all the world's coasts convey a power estimated to average in the order of 1 TW. This is about one third of the world's present consumption of electric power

The tidal fluctuations in the oceans are caused by gravitational forces from the sun and the moon. The influence cause a wave with a height of less than 1 m at a period of 12 hours and 25 minutes.

OCEAN THERMAL ENERGY CONVERSION (OTEC)

Approximately 25% of the solar energy reaching the earth is absorbed by the sea. In tropical and subtropical areas there is a considerable temperature difference between surface water (25ºC) and deep water (5ºC). In principle this temperature difference may be exploited by a thermodynamic cycle. The enormous heat capacity of the large water volumes involved ensures an even supply of energy.

GEOTHERMAL ENERGY

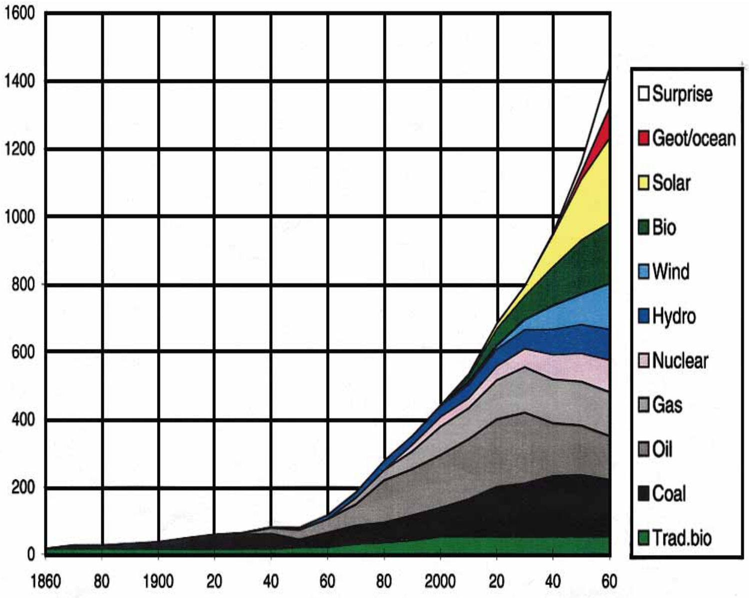
Large amounts of heat are generated within the earth's crust, mainly as a consequence of fission of radioactive material. In the centre of the earth the temperature is assumed to be 3000°C, and on average the temperature increases 30-35°C per km earth crust. The total heat amounts to approximately 35 billion times the world's annual energy consumption

In addition: Osmotic energy, hydro electric and many more

The Technology Gap

The overview of the available energy from renewable resources demonstrates quite clearly that there is sufficient energy potential to deliver all the energy we need from these resources. However, the challenge remains for us to develop sufficiently advanced technology to extract energy from these sources.

Some areas of energy extraction are more advanced than others, but clearly there is a potential that is not exploited. The figure shows expected changes in our sources of energy towards 2100.



Technology Gap II

The fact that we have had space exploration has lead many to think that anything can be done by technology at a minimal cost and development period.

Surely extracting energy from the ocean should be easy compared to that of sending a man to the moon?

Wind turbines have been used for centuries – what is new to develop?

Photovoltaic energy has low efficiency and is expensive.

Fuel cells are too expensive.

Why is the progress so slow I ?

Wave energy device destroyed by bad weather near Portugal

Some Reasons for slow progress

- Physics of devices is not well understood
- Inadequate modelling of device
- Financial return of device is poor, thus very little investment in device

In contrast, the space program was well funded by governments and the fundamentals of rockets and space travel was in comparison well understood.

MULTI-PHYSICS AND RENEWABLE ENERGY

In most engineering applications there are many diverse phenomena involved.

This also the case for engineering utilisation of renewable energy.

The efficient design, construction and optimisation of such engineering devices is necessary in order to ensure that hydro-carbon based methods are replaced as early as possible.

Multi-physics analysis, Multi-physics modelling and Multi-physics optimisation are therefore tools which can be used to speed up the application of renewable energy for an increasing percentage of energy requirements.

The aim of this presentation is to highlight some of the challenges within Multi-physics analysis and modelling to deal with typical renewable energy technology.

Outline of Multi-physics challenges

There are three major types of challenges:

- The understanding of each physical phenomenon involved in the extraction of renewable energy
- The understanding of the interactions between the relevant phenomena
- The modelling issues that arise from each of the physical phenomena and their possible interaction

Governing Principles

The Governing Principles for all phenomena related to renewable energy (or other issues) are as follows:

- Conservation of mass
- Conservation of momentum
- Conservation of energy

Governing Equations II

In order for the equations of previous slide to form the basis of a numerical model, there must be sub models appropriate for the energy devices. Typically these models would be dealing with:

- Turbulence
- Diffusivity
- Heat transfer
- Interactions between phases
- Cavitation
- Phase change

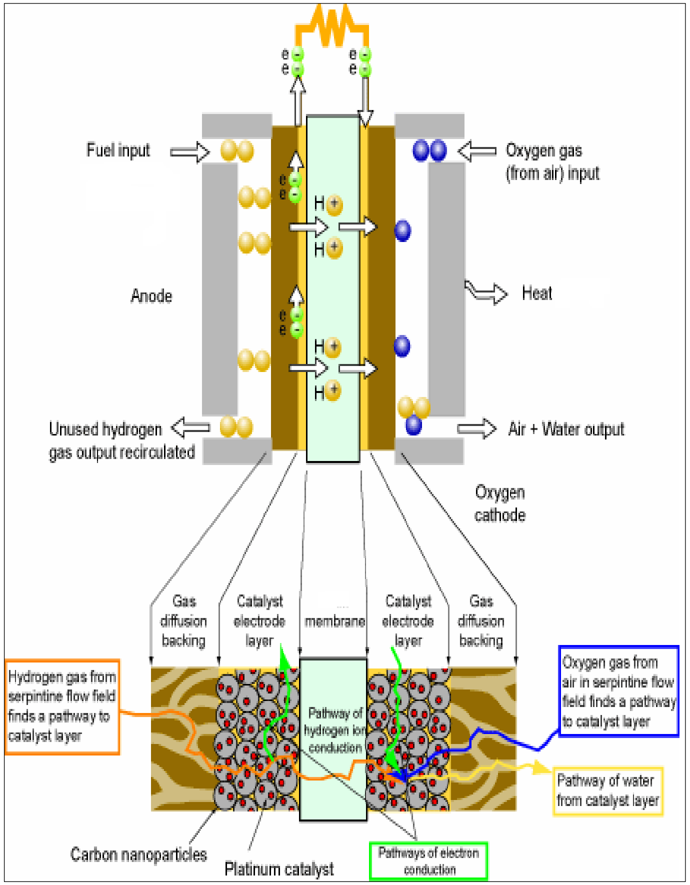
Governing Equations II

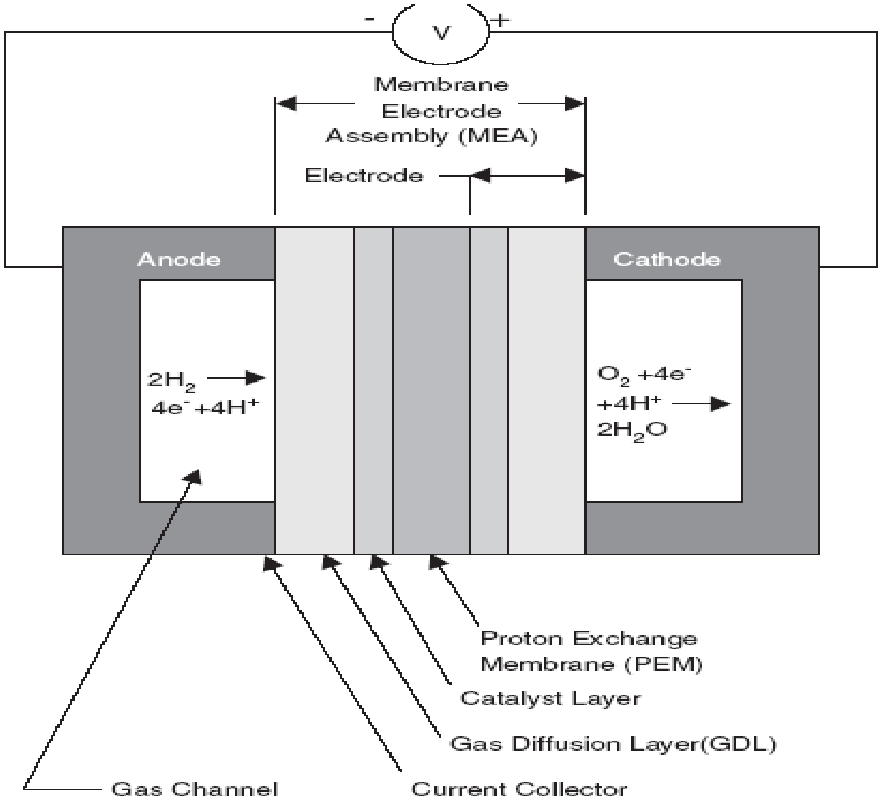
The equations are in general three dimensional, time dependent and non-linear which means that when dealing with issues based on them for design and optimisation purposes there are considerations such as:

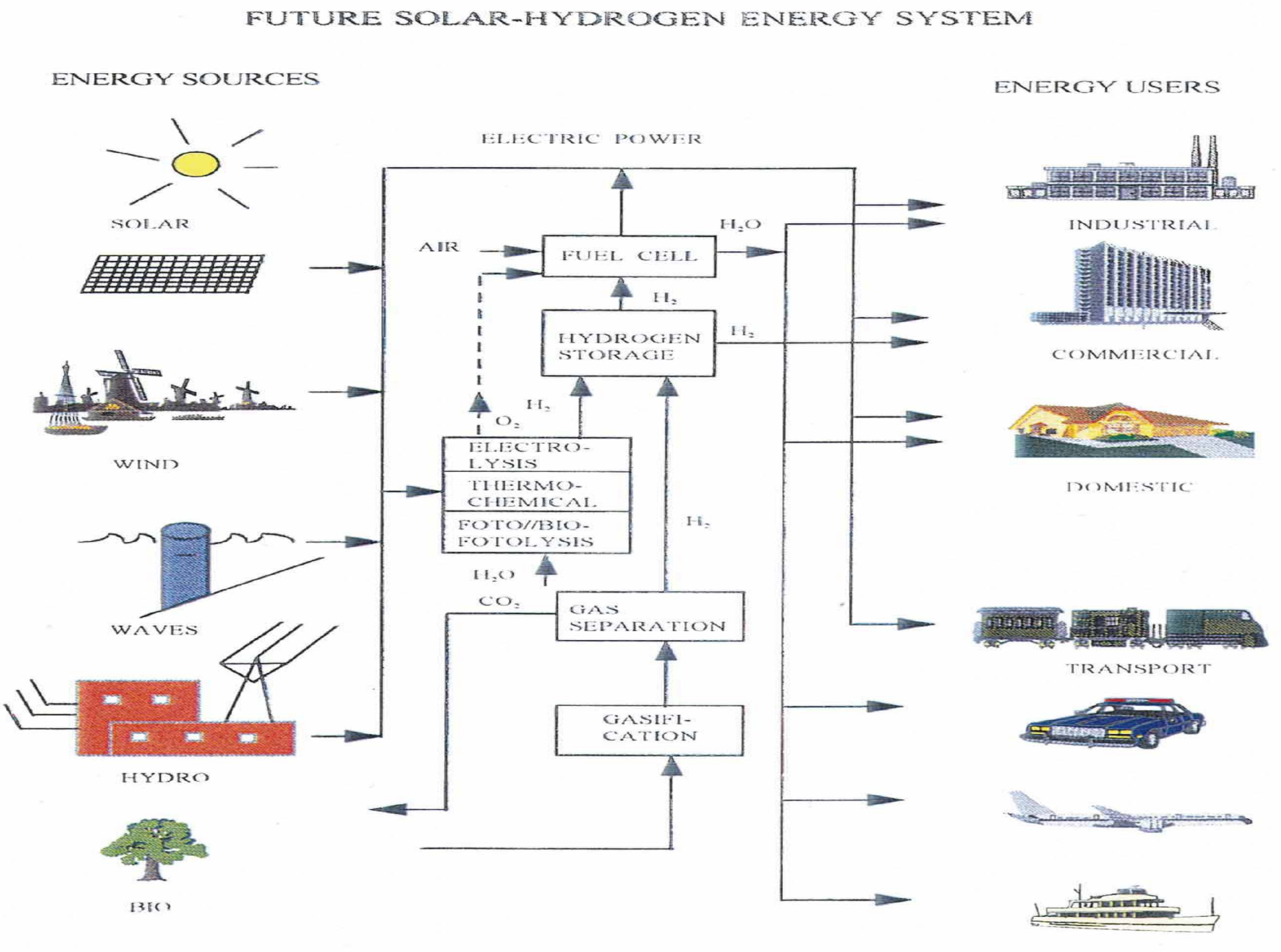
- Scaling in time and space
- Resolution of instrumentation or numerical schemes
- Meshing
- Scale models or full scale

This means that dealing with numerical simulations for Multi-Physics can be very demanding

An Example: The Proton Exchange Membrane (PEM)Fuel Cell



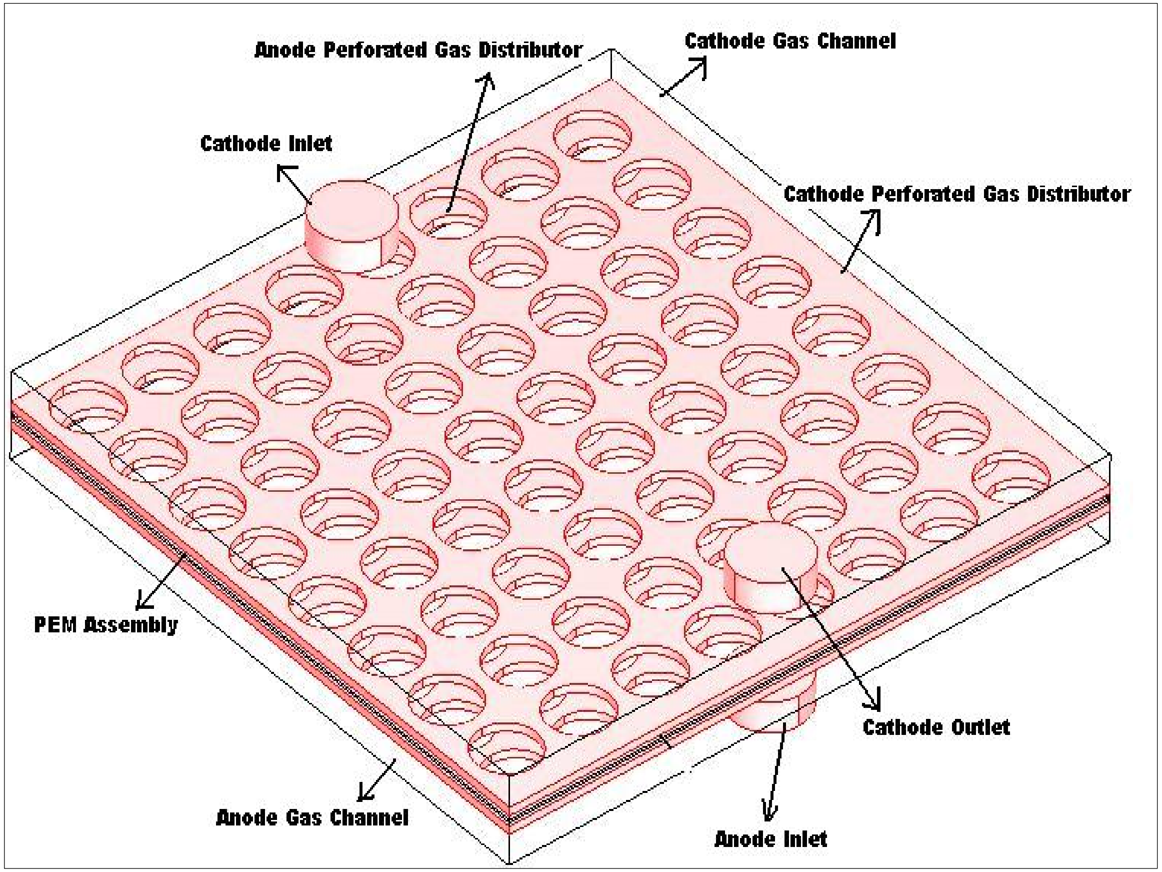



FUTURE SOLAR-HYDROGEN ENERGY SYSTEM
ENERGY SOURCES
ENERGY USERS
ELECTRIC POWER
SOLAR
WIND
WAVES
HYDRO
BIO
AIR
FUEL CELL
H2O
H2
HYDROGEN STORAGE
H2
H2
O2
ELECTRO-LYSIS
THERMO-CHEMICAL
FOTO//BIO-FOTOLYSIS
H2
H2O
CO2
GAS SEPARATION
GASIFI-CATION
INDUSTRIAL
COMMERCIAL
DOMESTIC
TRANSPORT

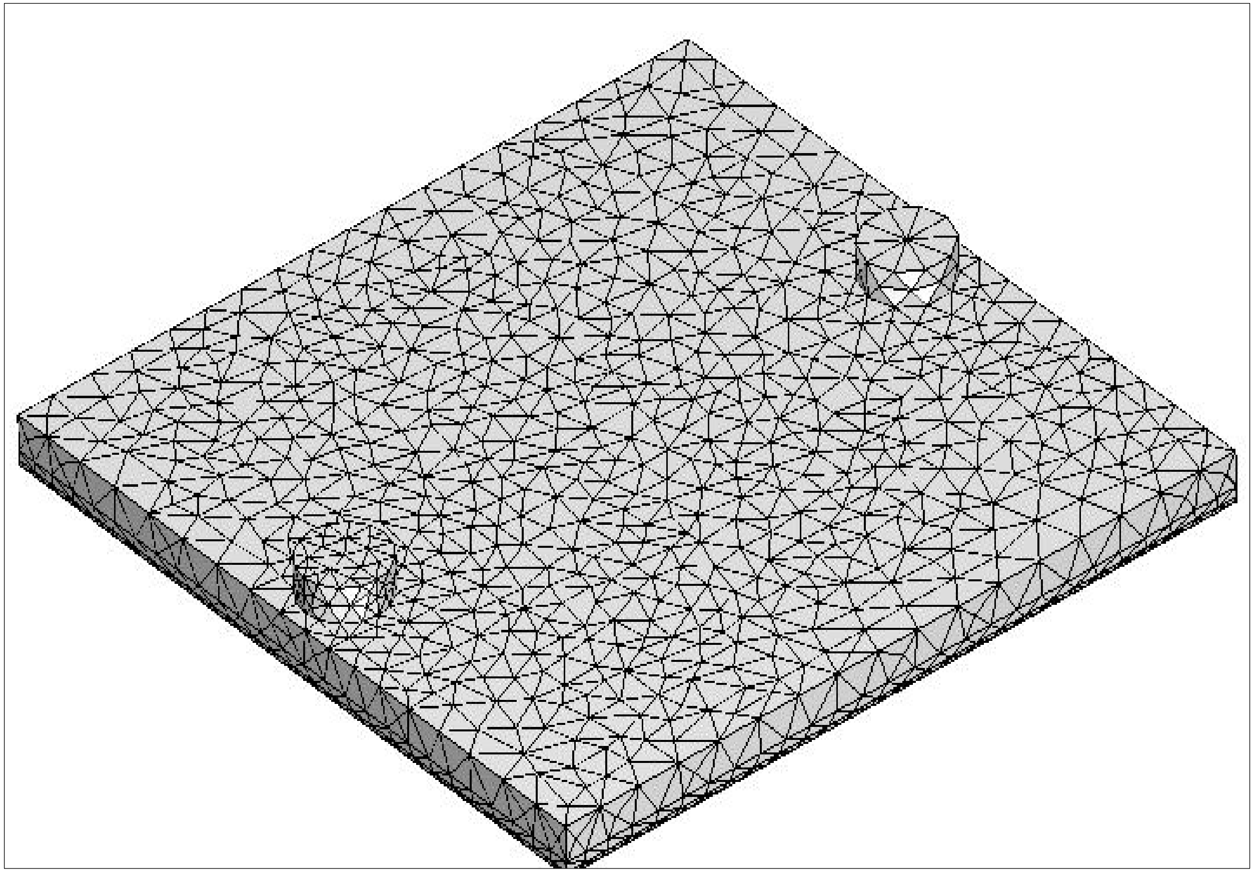
PEM Fuel Cell II

Cathode Gas Channel →	Momentum Conservation , Species Transport and Mass Conservation (Maxwell Stefan Diffusivity) , Energy Conservation (Heat Transfer)
Perforated Gas Distributor →	Momentum Conservation , Species Transport and Mass Conservation (Maxwell Stefan Diffusivity), Energy Conservation (Heat Transfer)
Gas Diffusion Layer →	Momentum Conservation , Species Transport and Mass Conservation (Maxwell Stefan Diffusivity with Bruggemann correction for porous media), Energy Conservation (Heat Transfer)
Cathode Catalyst Layer →	Momentum Conservation , Species Transport and Mass Conservation (Maxwell Stefan Diffusivity with Bruggemann correction), Charge Conservation (Butler-Volmer Equation), Energy Conservation (Heat Transfer)
Membrane →	Membrane water content related equations
Anode Catalyst Layer →	Momentum Conservation , Species Transport and Mass Conservation (Maxwell Stefan Diffusivity with Bruggemann correction), Charge Conservation (Butler-Volmer Equation), Energy Conservation (Heat Transfer)
Gas Diffusion Layer →	Momentum Conservation , Species Transport and Mass Conservation (Maxwell Stefan Diffusivity with Bruggemann correction for porous media), Energy Conservation (Heat Transfer)
Perforated Gas Distributor →	Momentum Conservation , Species Transport and Mass Conservation (Maxwell Stefan Diffusivity), Energy Conservation (Heat Transfer)
Anode Gas Channel →	Momentum Conservation , Species Transport and Mass Conservation (Maxwell Stefan Diffusivity), Energy Conservation (Heat Transfer)

PEM fuel cell CAD model



Course Mesh for Fuel Cell



Multiphysics modelling of the Fuel Cell

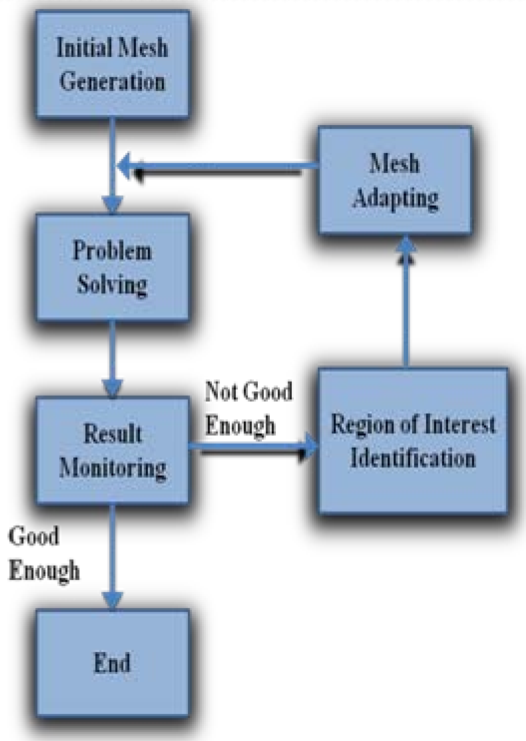
- Large number of equations to solve
- Many unknown coefficients
- Complex geometry
- Large mesh required
- Differing scales required for each phenomenon
- Coupling between equations may not always be clear

In summary a very demanding task both numerically and in terms of experimental information

Numerical considerations

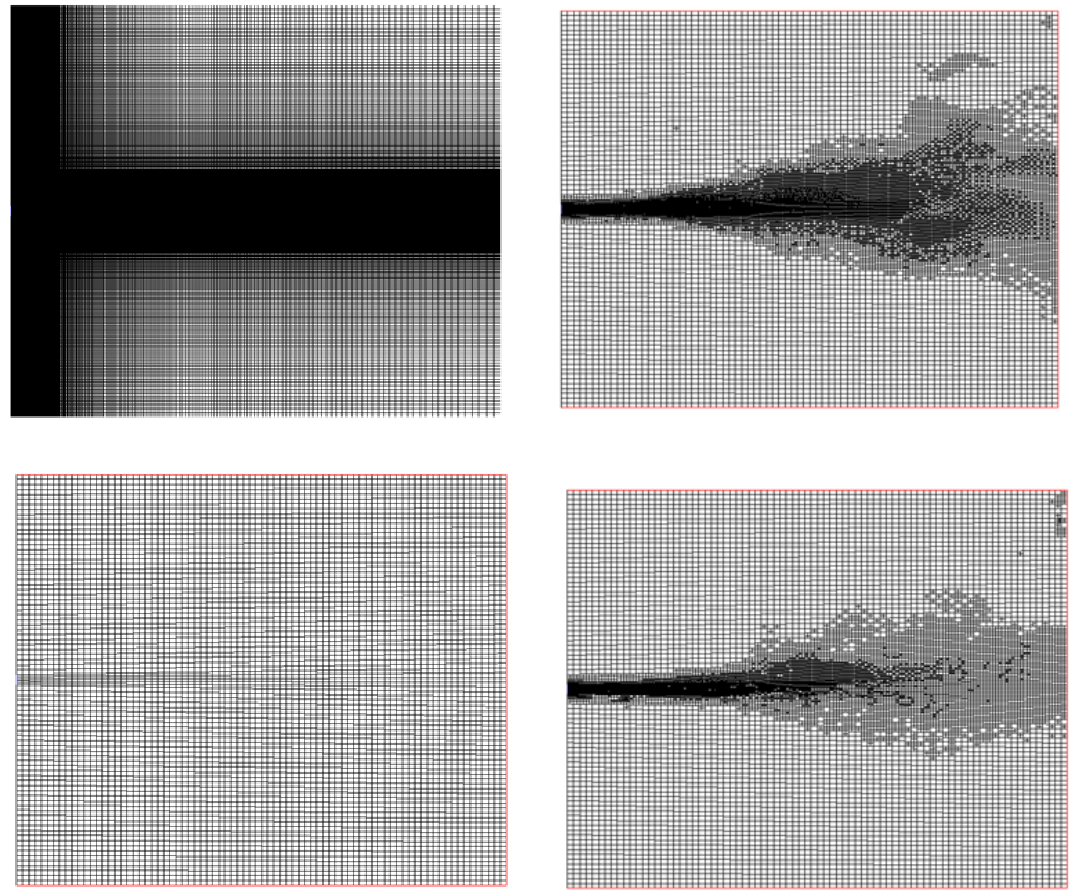
- High or Low order schemes
- Finite Volume (FV) or Finite Element (FEM) – bearing in mind that FV solves momentum both locally and globally whilst FEM solves only globally – is this important for multiphysics problems?
- Will mesh requirements be prohibitive for problems such as PEM Fuel Cell in 3D
- Can Solution adaptive grids be used?

Solution Adaptive Grids (SAG)

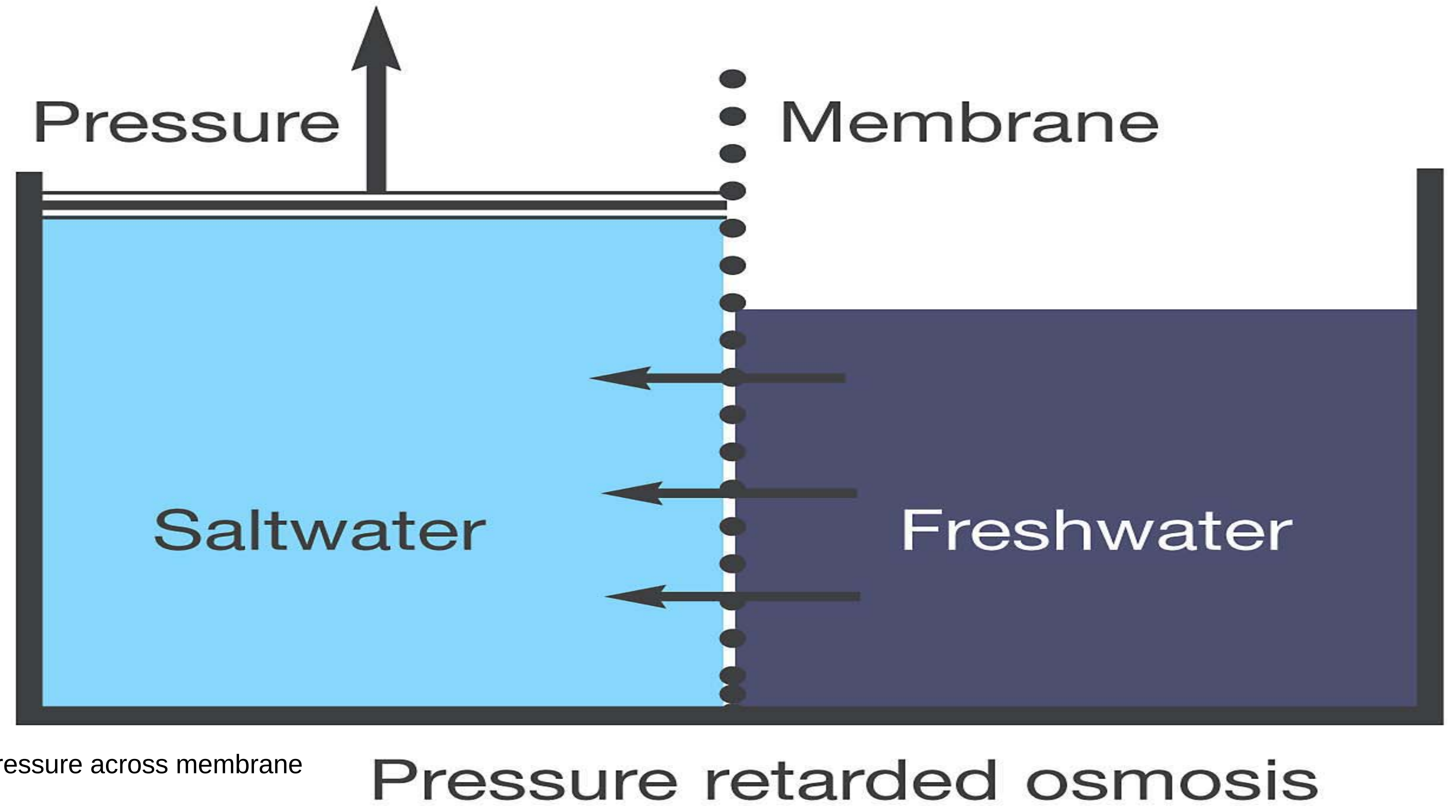


Procedures for SAG –Required fixed mesh for jet –

Solution adaptive meshes

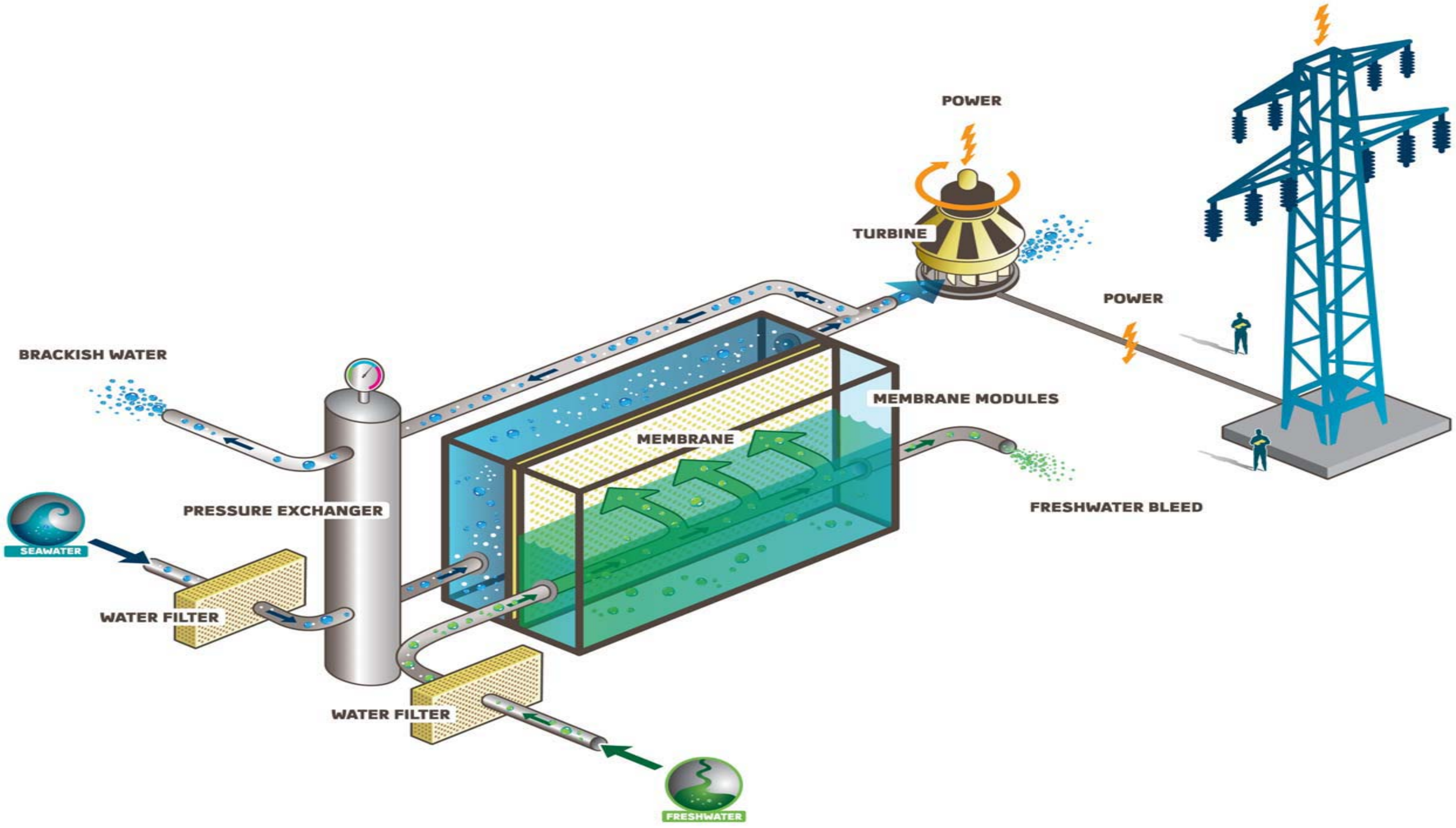


Another example: Osmotic Power



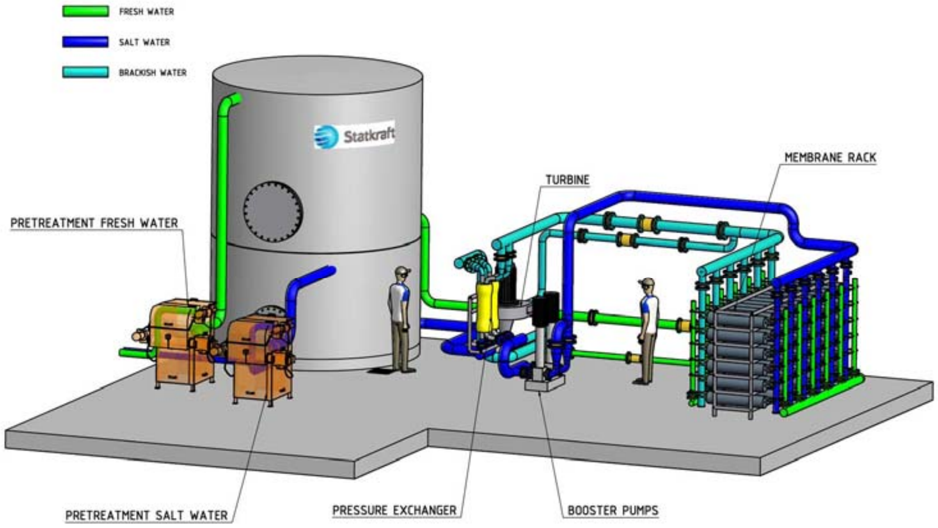
Osmotic pressure across membrane upto 120m

In the Osmotic pressure power station fresh and salt water enters through separate chambers and remain separated through an artificial membrane. The salt molecules in the seawater pull the freshwater through the membrane so that the pressureon the seawater side increases. The pressure increase will be near 120 m. This is close to pressure required of a large hydro electric powerstation. A turbine can be used to generate electricity.



Prototype Osmotic Power Station

Prototype power station has recently been commisioned



A Modelling Challenge

Common for both the Fuel Cell and the Osmotic Power Station is the membrane and its significance for the functioning of the devices.

A challenge is to represent the membrane in a realistic multi physics model

Wave and Tidal Energy

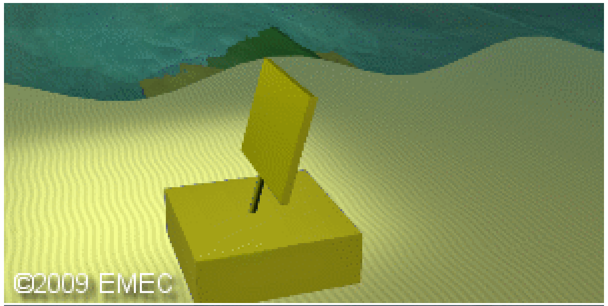
There are at present many prototype wave and tidal energy devices being tested. Many of these device have had significant design or performance problems.

Clear the use of multi- physics modelling should be used in order to improve the devices.

Range of Wave energy devices

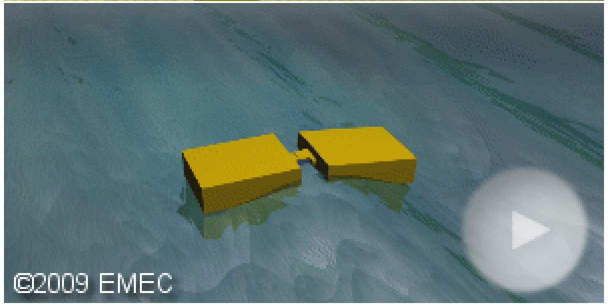
Oscillating Wave Surge Converter

This device extracts the energy caused by wave surges and the movement of water particles within them. The arm oscillates as a pendulum mounted on a pivoted joint in response to the movement of water in the waves. Fluid-Structure interaction (FSI) is clearly needed for modelling, but Reynolds numbers are large as are Strouhal numbers. Consequently experimental data is needed.



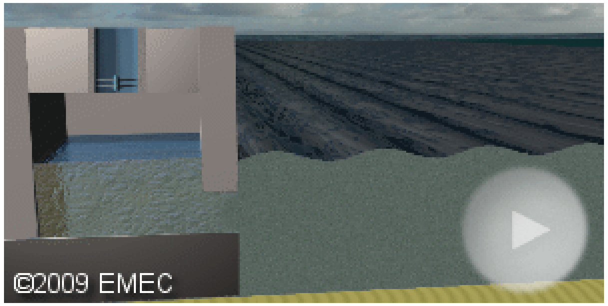
Attenuator

An attenuator is a floating device which works parallel to the wave direction and effectively rides the waves. Movements along its length can be selectively constrained to produce energy. It has a low area parallel to the waves so the device experiences low forces. Fluid-Structure interaction (FSI) is clearly needed for modelling, but Reynolds numbers are large as are Strouhal numbers. Consequently experimental data is needed.



Oscillating water column

An oscillating water column is a partially submerged, hollow structure. It is open to the sea below the water line, enclosing a column of air on top of a column of water. Waves cause the water column to rise and fall, which in turn compresses and decompresses the air column. This trapped air is allowed to flow to and from the atmosphere via a turbine, which usually has the ability to rotate regardless of the direction of the airflow. The rotation of the turbine is used to generateelectricity.



Many devices are designed for conditions where experimental data are not available

Tidal Energy

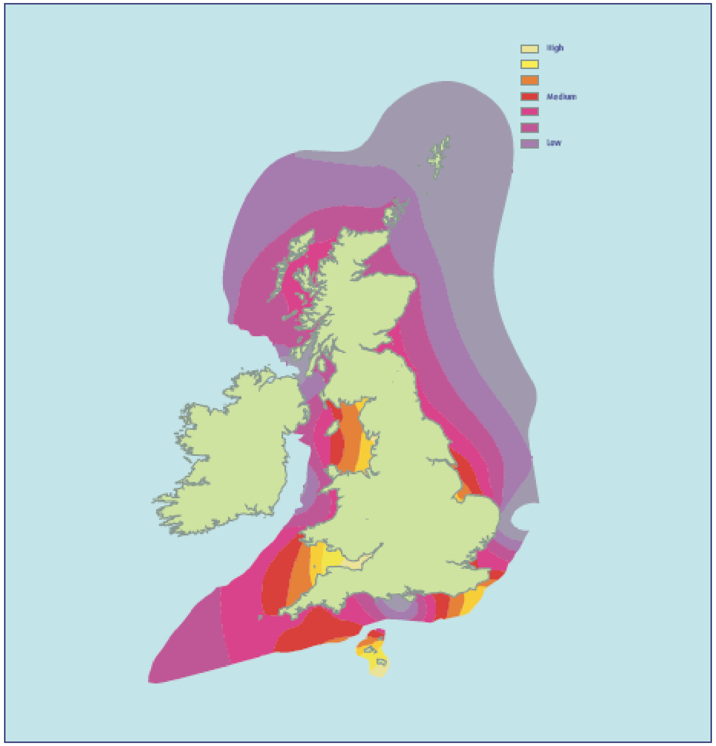
Tidal energy is a useful source of energy. Whilst wind and wave energy can be very unpredictable, tidal energy in contrast is very predictable since it is a function of the lunar cycle.

There have been several attempts at utilising tidal energy since the 1960's. There is a barrage in La Rance, France. The construction of this barrage began in 1960. The system used consists of a dam 330m long and a 22km2 basin with a tidal range of 8m, it incorporates a lock to allow passage for small craft. During construction, two temporary dams were built on either side of the barrage to ensure that it would be dry, this was for safety and convenience. The work was completed in 1967 when 24, 5.4m diameter Bulb turbines, rated at 10MW were connected to the 225kV French Transmission network. Very expensive to build

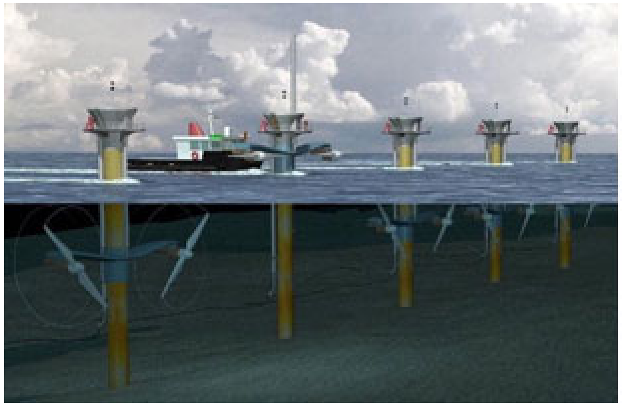
La Rance – Tidal Barrage

Tidal Energy II

Tidal barrages are clearly very expensive and they also constitute significant local environmental impacts. However, they may be suitable in areas such as the Severn Estuary.

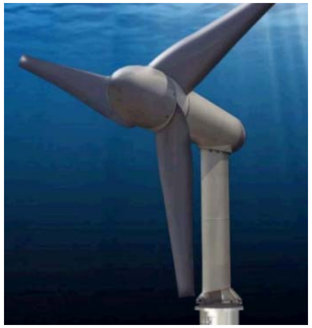


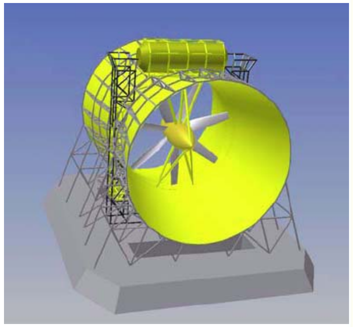
There are other developments in terms of Tidal Energy extraction which are similar to Wind turbines, but challenges to multi physics modelling are high Reynolds numbers and rotating devices with complex geometry together with FSI



Tidal Energy looks like the wind industry about twenty years ago

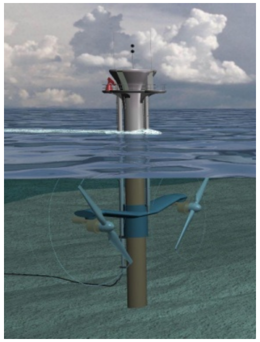
Status



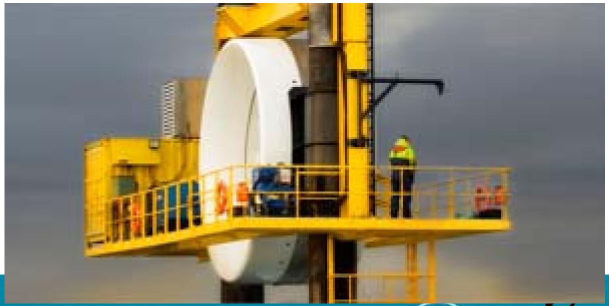


<u>State of the Industry</u>
Device Developers

- More than a dozen device developers
  - — Dominant design has yet to emerge
  - — Most developers are UK based due to significant government investment in marine renewables

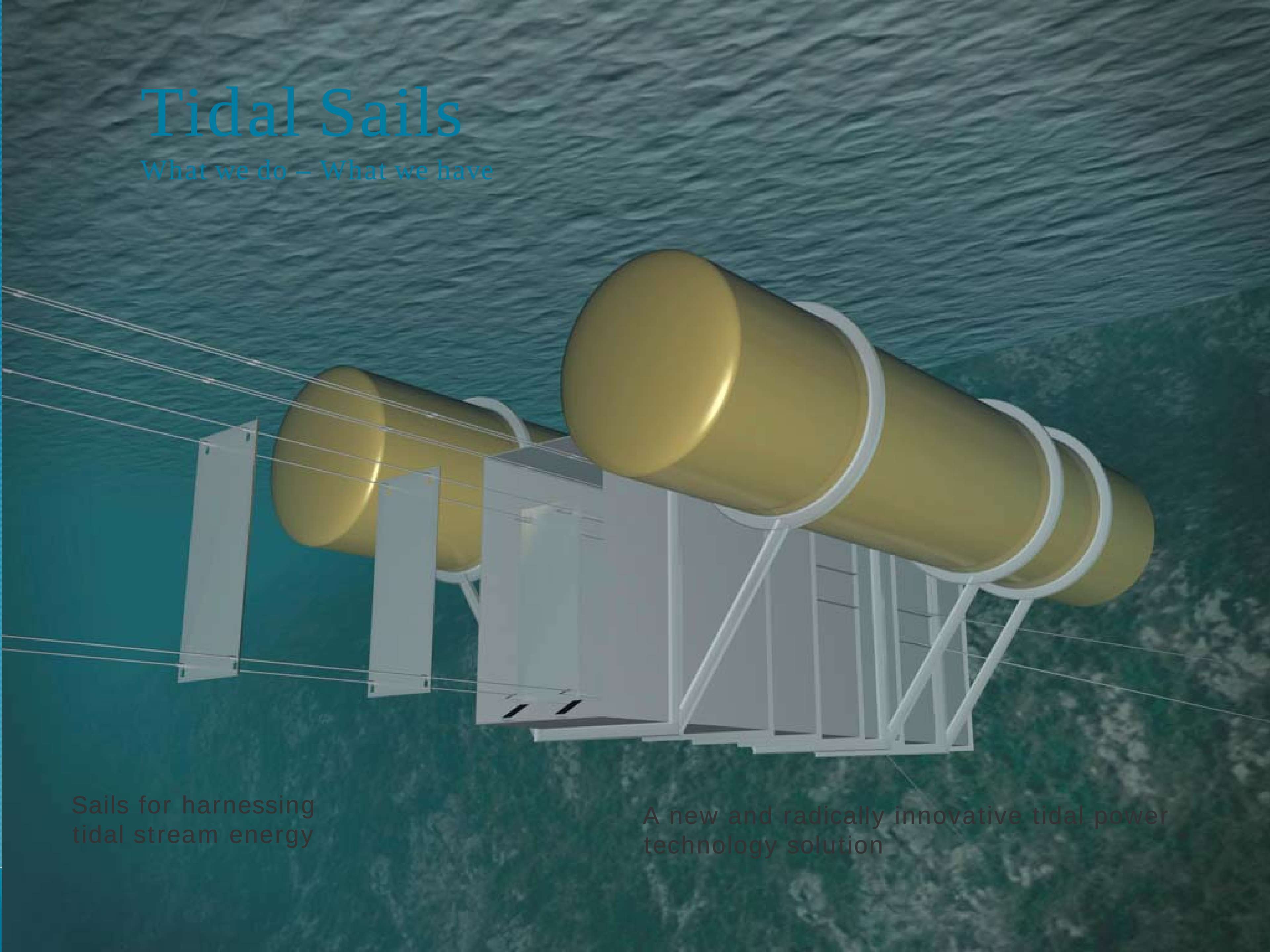


- Many developers have tested small-scale models
  - — Laboratory and field tests to verify expected performance
  - — Difficult to address “big picture” questions in the lab
- Full-scale testing just beginning
  - — 300 kW turbine in water in Devon, UK for three years (MCT)
  - — 1.5 MW turbine planned for Strangford, UK in 2008/2009 (MCT)
  - — 6 x 34kW turbine array permitted for East River, NY in 2007 (Verdant)
  - — kW scale ducted turbine at Race Rocks, BC (Clean Current)
  - — OpenHydro testing at EMEC (European Marine Energy Center) since December 2007



Tidal Sails

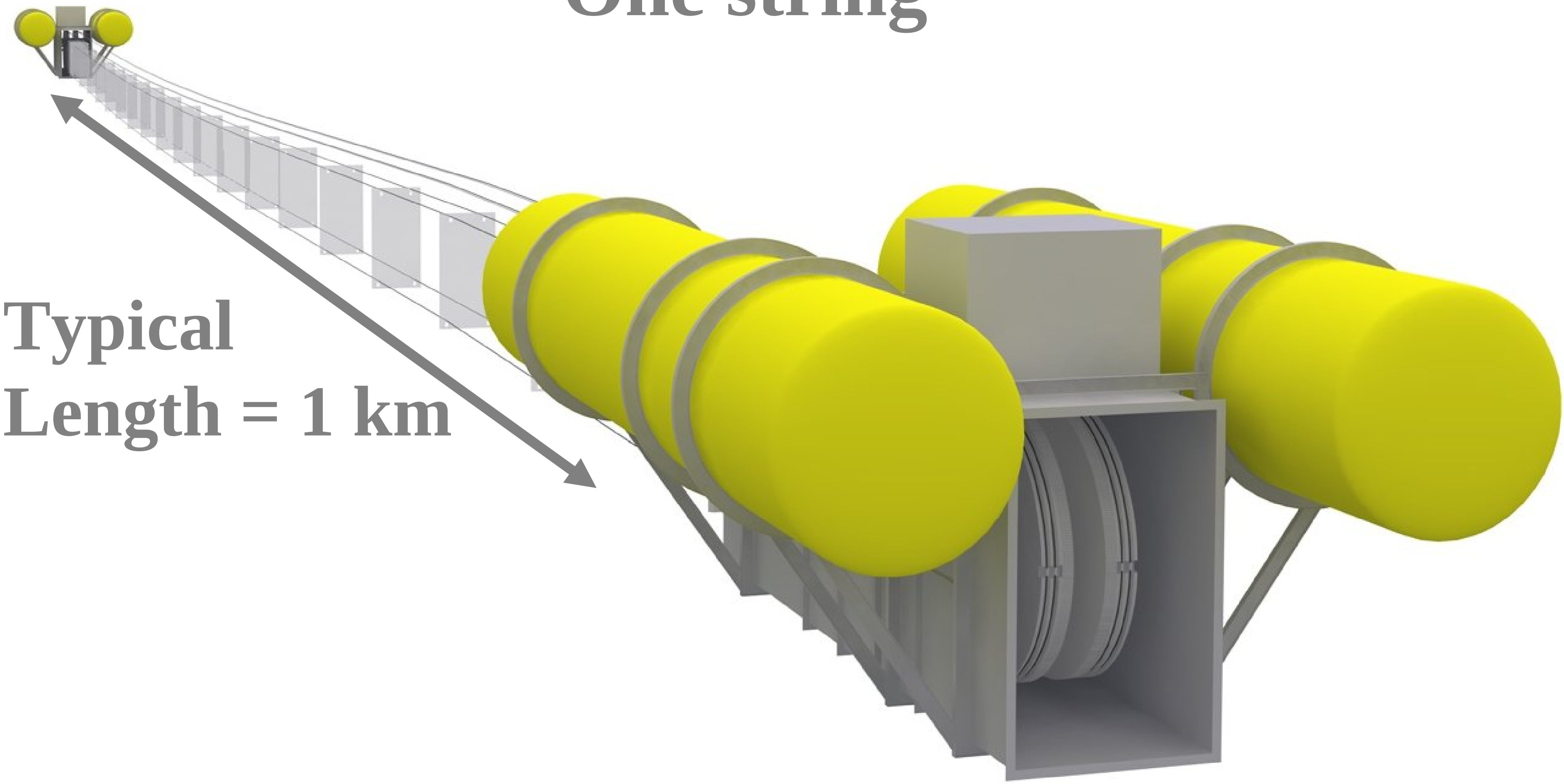
What we do – What we have



Sails for harnessing
tidal stream energy

A new and radically innovative tidal power
technology solution

One string



TIDALSAILS

Heat Devices

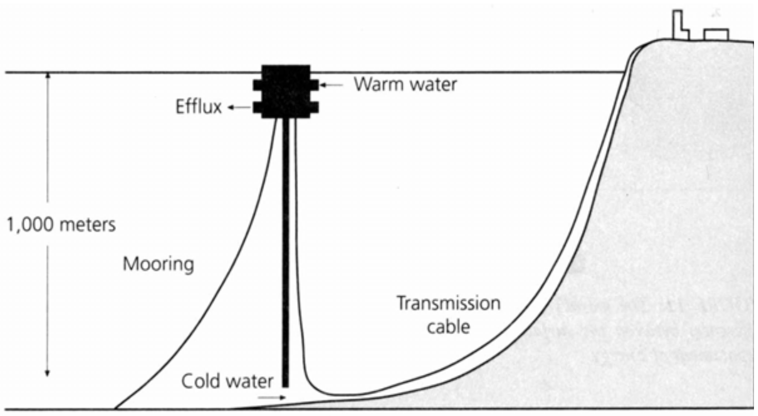
GEOLOGICAL STORED HEAT IN OSLO, NORWAY

This unique project deals with storage of energy in 180 wells drilled down to 200m. The wells perforates a rock o 1.800.000 m3 underneath the buildings (a University building, a block of flats and a shopping centre totalling 200.000 m2)Each well has connection to two other wells in series, so that there is a closed system. Cooling in summer time means pumping water to the wells for storage. During winter, the stored energy is used for heating.

The investment is expected to take 2.5 years to pay back The system deals with 7.5MW for heating and 9MW for cooling.

Multi-physics challenges are related to scale of model and heat transfer properties

Conceptual Renewable Energy Devices



OCEAN THERMAL ENERGY CONVERSION (OTEC)

The principle for OTEC is illustrated in the figure. The low conversion efficiency means that large quantities of water are needed. A 100 MW OTEC power station would need 450 m3 water per second, both on the hot and cold sides. Several demonstration plants have been constructed, the first one as early as 1930. At present, economy is the main obstacle to development of this technology. However, the environmental impact from large scale usage of OTEC is not well understood.

Multi-physics challenges relate to model scale and heat transfer

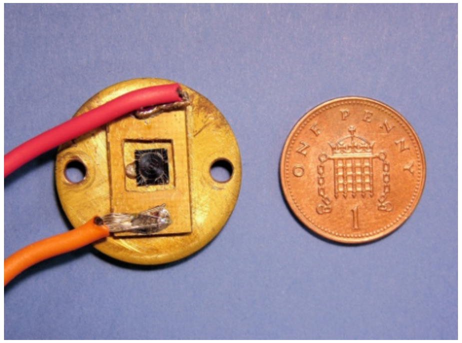
Photovoltaic Methods . Challenges: Radiation models

Novel Photovoltaic methods

- 63% of electricity in UK used in buildings
- Sunlight on buildings ~ 7x electricity consumption in the buildings
- DEMAND similar through year, peaks daily ~2x BASELOAD –

Solarstucture Ltd– new company for Building Integrated Concentrator PV

- Cells are very small (~ 1mm)
- high efficiency (~ 30%)
- need 500 x concentrators to reduce costs
- The concentrators must track the sun



- Curtain walls (glass facades) =>
- Use tracking blinds to cut direct sunlight to remove glare and reduce air conditioning demand
- Cell cooling to provide hot water
- Cell to provide electricty

Other technologies at Mature Stage

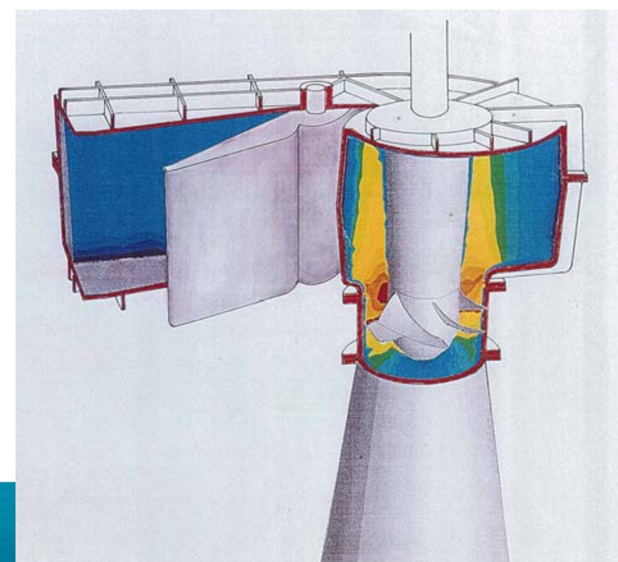
SMALL-SCALE HYDRO POWER

When the installed capacity of a hydro power plant is less than 10 MW, it is often characterised as "small". It is customary to define 3 categories of plants: micro (<100 kW), mini (100 - 1000 kW), and small (1 - 10 MW). The global installed capacity in hydro power plants amounts to 627 GW producing some 2300 TWh per year. Of this, small scale hydro is estimated to 19.5 GW and 80 TWh respectively.

Many rivers and streams are well suited for such small hydro power installations, and in large parts of the world there is a need for electric power in remote areas. Only 5% of the world population living in remote areas can expect to be supplied through utility grids.

The technology is well known and proven, and the installations are simple and an important part of the plant can be of local origin (civil works, buildings). However, in small projects the specific investment cost tend to be high, typically 1200 - 3000 Euro/kW (1500 - 3800 US$/kW), and there is need to train the personnel that run the plant. In order to increase the viability of small scale hydro power it is necessary to develop the technology in order to take advantage of the scale effects of larger production series.

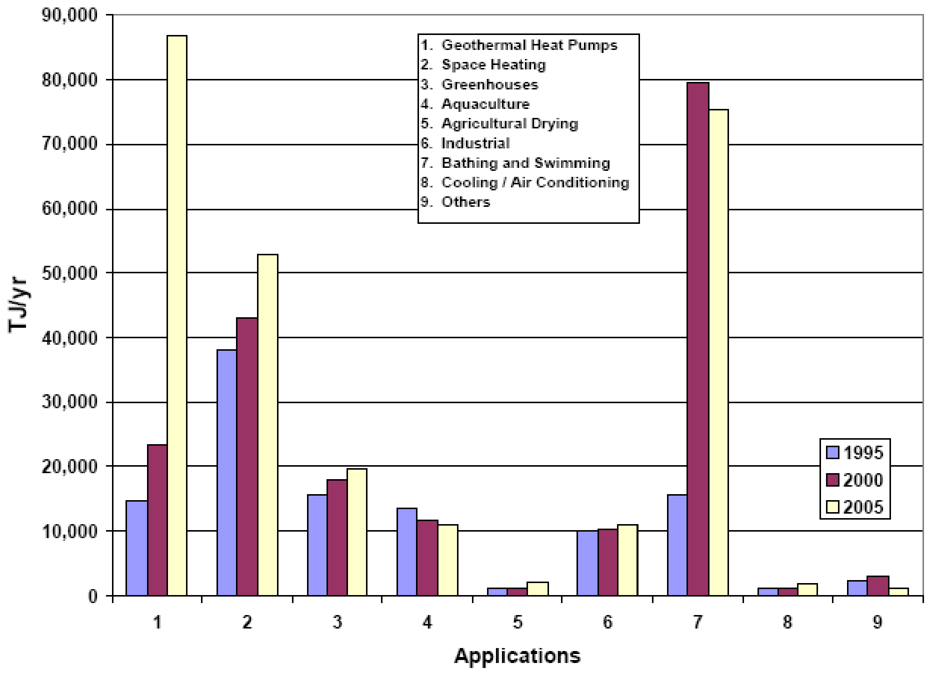
For small sites, complete power station units are built in cargo containers. These units are easy to install with respect to foundation work, water supply (penstock), grid connection etc.



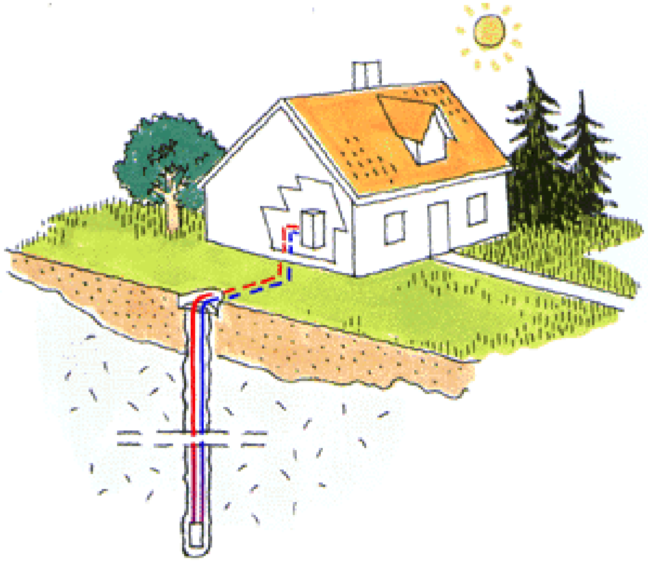
Other technologies at Mature Stage II

Heat Pumps

The figure below shows the world wide applications of heat pumps



House with heat pump



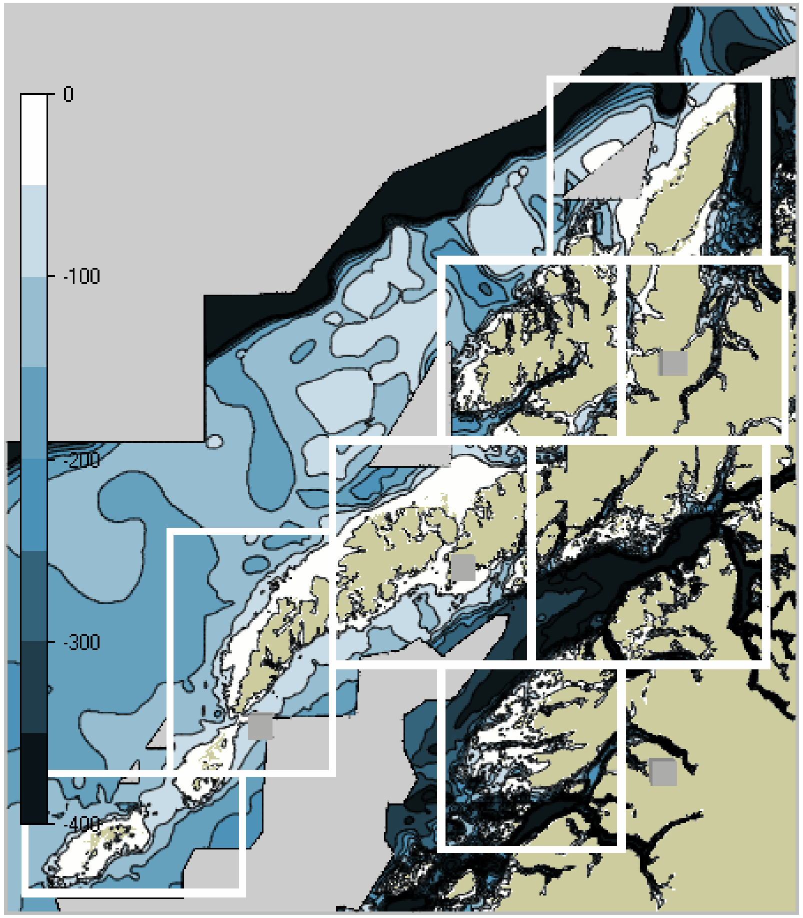
Other technologies at Mature Stage III

THERMAL SOLAR ENERGY

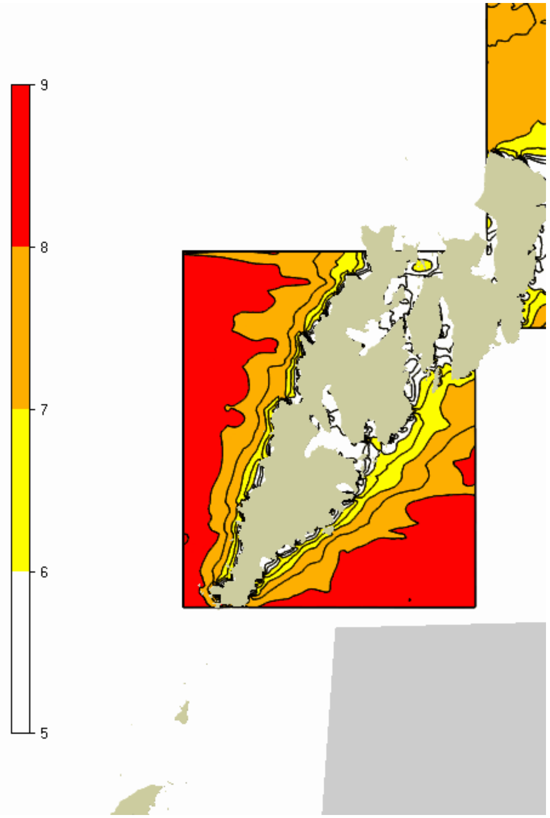
Typical application of solar panels to heat domestic water

Photo voltaic cells are available but still expensive

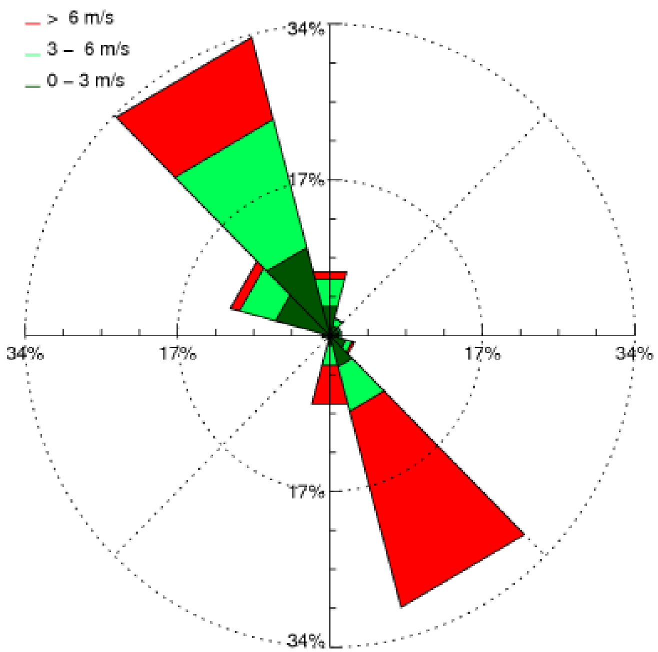
Wind Energy and Wind atlas



Average wind speed at 50m



Choosing a site

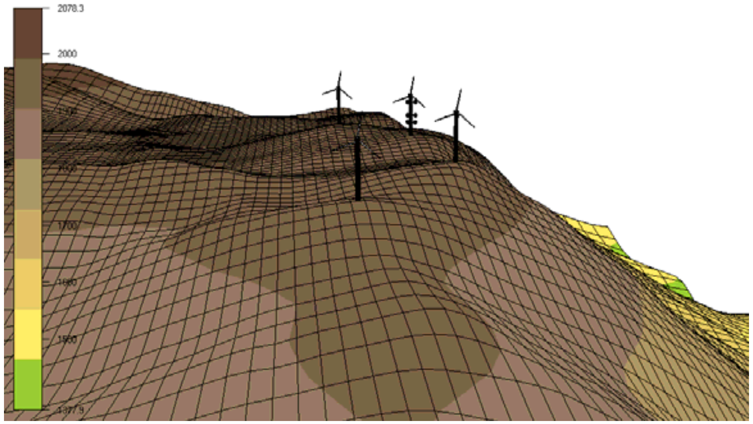


Wind rose showing directional properties of wind during a year. This information also aids to locate best site for wind turbines,

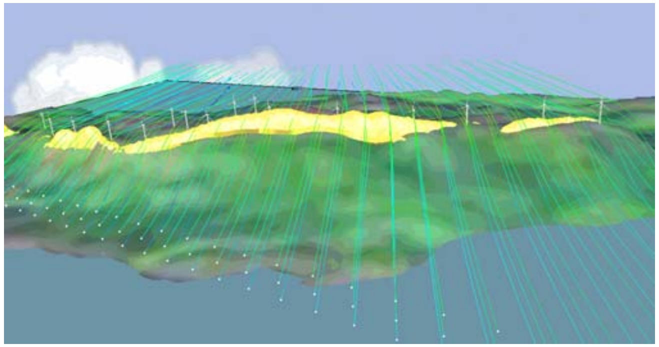
Choosing a site II

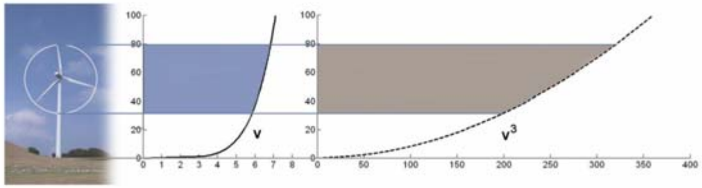
CAD model of terrain followed by CFD model

Terrain model

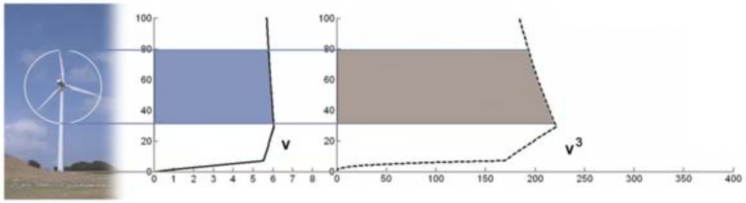


Model results





Ideal power content



Actual power content

Høgskolen i Narvik

Wind Energy

Modern wind turbines are more than 80 m in diameter (more than wing span of 747 or A380). Bearings need frequent replacement possibly due to wind shear. Present turbines are upto 3 MW

Larger wind turbines are planned.

Single Physics Issues

- Many devices are designed for loading conditions where experimental data for operating range of important parameters are not always available
- Costs of full scale data are prohibitive for many developers
- Reliance on inexpensive numerical modelling
- Many models which form part of numerical packages may not always be validated for relevant device operating conditions

Multi physics issues

- Membrane modelling
- Multi-phase modelling
- Phase change modelling
- Coupling between physics
- Range of dimensionless groups

SUMMARY

Many new devices are being developed for renewable energy based on a variety of methods. In some cases the methods are not understood sufficiently for good modelling and a considerable amount of experimental data is required.

Due to poor control of data many devices are destroyed or expensive to operate

The multi-physics community should endeavour to approach FP7 or other grant issuing authorities in order to get funding to obtain better data and to develop improved numerical methods where appropriate.

Thank You for Your Attention!

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