Vanadium redox-flow batteries - Installation at Risø for characterisation measurements

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Energy Implications of Climate Mitigation Policies, Massimo Tavoni, FEEM

Promotion strategies for electricity from renewables in the EU–lessons learned, Reinhard Haas, Vienna University of Technology

Session 2 - Scenarios and Policy Options

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Integrated European Energy RTD as part of the innovation chain to enhance renewable energy market breakthrough, Peter Lund, Helsinki University of Technology

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Vanadium redox-flow batteries – Installation at Risø for characterisation measurements, Henrik Bindner, Risø National Laboratory, the Technical University of Denmark
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Solid Oxide Electrolysis for Fuel Production, Sune D. Ebbesen, Anne Hauch, Søren H. Jensen, and Mogens Mogensen, Risø National Laboratory, the Technical University of Denmark

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Fuel Cell - Shaft Power Packs, Frank Elefsen, Danish Technological Institute

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Overview of U.S. DOE’s Coal RD&D Programs, Scott M. Smouse, National Energy Technology Laboratory, Office of Fossil Energy, U.S. Department of Energy

The UK Energy Research Atlas: A Tool for Prioritising and Planning Energy R&D, Jim Skea, Research Director, UKERC

European and global perspectives for CCS, Martine Uyterlinde, Heleen Groenenberg, Energy Research Centre of the Netherlands

Solar Energy, Status and Perspectives, Peter Ahm, Director, PA Energy A/S
Energy Efficiency
Achieving more with less

Risø International Energy Conference
Roskilde, 22 May 2007

Stefan Denig, Siemens AG
Challenges:
Climate change is a fact, threatening humans and biosphere

- Climate change and impact
  - Anthropogenic greenhouse gas emissions 1) from fossil fuel burning and land use shift the radiation balance of the earth and cause warming
  - Scientific consensus that doubling of CO₂ from pre-industrial levels (280 ppm) by non-acting till 2035 causes unacceptable global temperature increase
  - Feedback amplifies warming

- ... threatens humans and biosphere
  - Melting may cause flooding of >4 million km² affecting >300 million people
  - Spread of diseases expected (Malaria, Dengue fever etc.)
  - More frequent extreme weather conditions jeopardize crops and living conditions
  - 15-20% of species face extinction at only 2°C warming

1) Carbon dioxide, methane, nitrous oxides, etc.

Effect of greenhouse gases

Urgent need for action

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Challenges:
Business as usual will be more costly than action

- Long-term cost of inaction (Business as usual) and action

<table>
<thead>
<tr>
<th>Business as usual scenario 2050 (Cost of inaction)</th>
<th>Action scenario 2050 ²) (Cost of action)</th>
</tr>
</thead>
<tbody>
<tr>
<td>% of global annual GDP in a case without global warming</td>
<td>% of global annual GDP in a case without global warming</td>
</tr>
<tr>
<td>20%</td>
<td>0.05-0.5% adaptation</td>
</tr>
<tr>
<td>5%</td>
<td>ca. 1.5%</td>
</tr>
<tr>
<td>Incl. additional impacts (e.g. amplifying feedback, non-market impact)</td>
<td>1% mitigation</td>
</tr>
</tbody>
</table>

Climate change has serious impacts on growth and development

The costs of stabilizing the climate are significant but manageable

1) Assumes 5°C temperature increase by 2050
Source: Stern Review

2) Keep GHG between 500 and 550 CO₂e ppm

1) Assumes 5°C temperature increase by 2050
Source: Stern Review

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Challenges:
Highest CO₂ emissions in North America and Asia

Population size times average annual per capita emissions. The size of the circles indicates the product of these variables and therefore the region’s total CO₂ emissions in 2000 and 2020.

- GHG emissions – responsible for global warming – will increase
- Level of GHG emissions will remain high in industrialized countries, but will increase particularly in emerging countries.

Source: EC 2003

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Challenges:
Rapidly increasing energy consumption, mainly in BRIC countries

Most rapid growth expected in non-OECD countries

- Fastest growth evident in BRIC economies
- Growth driven by industrialization and rising per capita consumption, although per capita consumption remains at low level
Challenges:
Large growth of world final energy consumption

Growing consumption of natural resources

- Energy consumption is rising dramatically
- Fossil fuels to remain of vital importance
- Ongoing growth in the demand for oil, gas and coal
Challenges:  
Coal will last the longest

Ensuring the supply of resources

- Improve production infrastructure in order to assure supply
- Manage political crisis
- Promote diversification in order to guarantee long-term supply
- Promote renewable energy use on individual level
Challenges: 
Growing relevance of energy security

Political implications

- Energy supply questions are entering the political agenda: Nationalization of energy industries (e.g. in Russia, Bolivia, Venezuela)

- China: Energy supply is vital for economic development (e.g. contracts with Iran to secure supply create dependencies and influence diplomatic behavior)

- Inter-regional trade of energy resources increasingly important (international attention will focus on maintaining the security of sea-lanes and pipelines)

Managing political conflict

- Challenge of fair resource supply needs to be addressed
- Conflicts have to be prevented
Challenges:
Energy diversity will not change fundamentally in the next 10 years

- Increasing importance of energy diversity

  Energy diversity will have to be a more prominent issue on the political agenda
  Use of renewables to expand diversity of supply
  Development of other alternative energy sources
### Solutions:
Achieving more with less

<table>
<thead>
<tr>
<th>Energy generation</th>
<th>Energy transmission</th>
<th>Energy consumption</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wind power</td>
<td>Solar thermal power</td>
<td>Energy saving motors</td>
</tr>
<tr>
<td></td>
<td>Photovoltaic</td>
<td>Energy saving bulbs</td>
</tr>
<tr>
<td></td>
<td>Post combustion CO₂-capture</td>
<td>Building as power plant</td>
</tr>
<tr>
<td></td>
<td>Pre combustion CO₂-capture</td>
<td>New materials</td>
</tr>
<tr>
<td>Efficiency of power plants</td>
<td></td>
<td>Performance contracting</td>
</tr>
<tr>
<td>Remaining time of nuclear power plants</td>
<td></td>
<td>Superconductivity in drives</td>
</tr>
<tr>
<td></td>
<td>Smart grids</td>
<td>Piezoelectric injectors in combustion engine</td>
</tr>
<tr>
<td></td>
<td>High Voltage DC Transmission</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Horizon</th>
</tr>
</thead>
<tbody>
<tr>
<td>Today – 5 years</td>
</tr>
<tr>
<td>5 - 15 years</td>
</tr>
<tr>
<td>15 - 50 years</td>
</tr>
</tbody>
</table>
Solutions:
Energy generation - Efficiency of up to 60% is possible

World's largest and most efficient gas turbine:

• Can supply electricity to 620,000 three-person households or a city the size of Barcelona, Spain

• Combined-cycle power plant with this gas turbine will have an efficiency of over 60% – world record

• In comparison with a coal-fired power plant (average efficiency 38%), it saves 2.8 million tons of CO₂ per year – more than Siemens emits

Shanghai – Efficient coal plant Waigaoqiao:

• China's largest and most modern coal-fired power plant, two 900 MW blocks installed, third in preparation

• Efficiency 42 percent (scheduled to rise to 45), highest of it's kind in China (average efficiency of black coal power plants in Germany: 37 percent)

• Sets also new standards in low-level nitrogen oxide and sulfur dioxide emissions
Solutions:
Energy transmission – HVDC enables use of remote sources

Low loss connection of remote power sources:

- Low energy loss in long distance power transmission (e.g. coal and hydro power (e.g. China), offshore wind parks in Europe
- Opens up large renewable power potential worldwide
- Allows for decoupling of power generation and load centers
- Flexibility in power sourcing and trading

Grid connection

> 80 - 120 km: HVDC
< ca. 80-120 km: AC
Solutions:
Energy consumption – Huge potential for energy savings

New Siemens trains use 30% less energy than Oslo's current trains:
- Less energy needed by feeding braking energy back into power grid and by using mostly aluminum for the lightweight body design
- Comprehensive disposal concept: 95% of each train can be utilized (85% through recycling, 10% through burning)
- Over their entire lifecycle the trains burden the environment with just 2.6 grams of CO₂ per kilometer traveled and per ton of vehicle weight – a very low value for metros (2.0 grams for actual train operation, depending on energy mix)

Energy saving bulbs use 80% less electricity:
- Lighting accounts for 19% of power demand worldwide
- Life of energy saving bulbs is up to 15 times longer than life of conventional bulbs; LED’s life is up to 50 times longer
- Savings per energy saving bulb and LED: several hundred euros p.a. and 0.5 t of CO₂
Increasing awareness:
Environment in top tier of megacities’ infrastructure priorities

Need for Investment
Average % of “Very High” Across All Cities (522 key decision makers in the 25 largest cities worldwide)

Source: Siemens Megacity Report 2007
Increasing awareness: Environment matters...

Mass transit is the priority
Predicted by transport experts

Strong role for renewables
Predicted by electricity experts

Source: Siemens Megacity Report 2007
Increasing awareness:
... but may be sacrificed for growth

Views of knowledgeable stakeholders

Source: Siemens Megacity Report 2007
The efficiency champion: How to reduce megacities’ energy consumption and CO₂ emissions with technolog. innovations
Energy balance-sheet of a virtual German megacity – What are the levers to reduce energy consumption?

10 million inhabitants, energy data from 2004

<table>
<thead>
<tr>
<th>Energy-related CO₂ emissions</th>
<th>Total primary energy supply</th>
</tr>
</thead>
<tbody>
<tr>
<td>106 million tons of CO₂ per year</td>
<td>1750 PJ per year</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Energy source</th>
<th>Energy (PJ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hard coal</td>
<td>228 PJ</td>
</tr>
<tr>
<td>Brown coal</td>
<td>201 PJ</td>
</tr>
<tr>
<td>Crude oil</td>
<td>630 PJ</td>
</tr>
<tr>
<td>Natural gas</td>
<td>403 PJ</td>
</tr>
<tr>
<td>Nuclear energy</td>
<td>220 PJ</td>
</tr>
<tr>
<td>Wind/water/others</td>
<td>68 PJ</td>
</tr>
</tbody>
</table>

| Losses during energy generation and distribution as well as consumption in the energy supply chain: | 630 PJ = 36% |

20% of energy needed as electricity. Equals 38% of primary energy!

58% of energy needed for heating!

28% of energy needed as motor fuels (20% for passenger cars)

Siemens’ total emissions: 2.7 million tons in 2005
**Possible scenario of tomorrow’s megacity**

Virtual German Megacity – tomorrow
Many measures are realized regarding efficiency increase and energy savings

<table>
<thead>
<tr>
<th>Site energy consumption today: 1120 PJ per year</th>
<th>More efficient and energy-saving systems</th>
<th>Lower losses of primary energy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Industry + Business 470 PJ</td>
<td>HVAC systems -30%</td>
<td>Total primary energy supply tomorrow: 860 PJ (minus 51%)</td>
</tr>
<tr>
<td>Process heat 198 PJ</td>
<td>Lighting -80%</td>
<td>Hard coal 228 PJ</td>
</tr>
<tr>
<td>Electricity 150 PJ</td>
<td>Process heat optimized prod. -20%</td>
<td>Brown coal 80 PJ</td>
</tr>
<tr>
<td>HVAC systems 270 PJ</td>
<td>Energy-saving motors -20%</td>
<td>Crude oil 280 PJ</td>
</tr>
<tr>
<td>Electricity 60 PJ</td>
<td></td>
<td>Natural gas 280 PJ</td>
</tr>
<tr>
<td>Households 330 PJ</td>
<td>HVAC systems -30%</td>
<td>Others*: 100 PJ</td>
</tr>
<tr>
<td>HVAC systems 350 PJ</td>
<td>Lighting -80%</td>
<td>Wind/power generation, solar, geothermal/biomass/waste</td>
</tr>
<tr>
<td>Electricity 60 PJ</td>
<td>Process heat optimized prod. -20%</td>
<td></td>
</tr>
<tr>
<td>Industry + Business 350 PJ</td>
<td>Energy-saving motors -20%</td>
<td></td>
</tr>
<tr>
<td>Site energy consumption tomorrow: 710 PJ per year (minus 37%)</td>
<td>HVAC syst. 80 PJ</td>
<td>Lower losses of primary energy</td>
</tr>
<tr>
<td>Energy-efficient power plants (efficiency of a combined-cycle power plant 60%, coal-fired power plant 48%)</td>
<td>HVAC systems -30%</td>
<td>Total primary energy supply tomorrow: 860 PJ (minus 51%)</td>
</tr>
<tr>
<td>More efficient household appliances -30%</td>
<td>HVAC systems -30%</td>
<td>Hard coal 228 PJ</td>
</tr>
<tr>
<td></td>
<td>Old building renovation, heat insulation -56%</td>
<td>Brown coal 80 PJ</td>
</tr>
<tr>
<td></td>
<td>New buildings as low energy or passive houses -70%</td>
<td>Crude oil 280 PJ</td>
</tr>
<tr>
<td></td>
<td>Lighting -80%</td>
<td>Natural gas 280 PJ</td>
</tr>
<tr>
<td></td>
<td>More efficient household appliances -30%</td>
<td>Others*: 100 PJ</td>
</tr>
<tr>
<td>Transportation 320 PJ</td>
<td>Motor fuels 313 PJ</td>
<td>Wind/power generation, solar, geothermal/biomass/waste</td>
</tr>
<tr>
<td></td>
<td>Electricity 7 PJ</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*can be reduced even more, if nuclear energy and CO₂ sequestration are used.
Energy Implications of Climate Mitigation Policies

Massimo Tavoni, FEEM
• The WITCH model
• Cost-benefit glimpse
• Climate mitigation policies
  – energy
  – costs vs delaying
  – uncertainty
WITCH

World Induced Technical Change Hybrid model

Hybrid I.A.M.:
- **Economy**: Top-down optimal growth (inter-temporal)
- **Energy**: Energy sector detail (technology scenarios)
- **Climate**: Damage feedback (global variable)

![Diagram of the WITCH Model]

- Economic Activity
  - Energy Use
  - Temperature
  - Emissions

The WITCH Model/1
Two solutions:

- **Cooperative** (world best)
- **Non-cooperative** (Nash), interactions among regions on:
  - Environmental externality (carbon)
  - Exhaustible resources (oil, gas, coal, uranium)
  - Technological spillover
  - Trade of emission permits
C.B.A.
non-coop vs coop
World Carbon Emissions

CO2 Emissions in main areas

- OECD
- TE
- DEVELOPING COUNTRIES

GtC

non-coop
World Carbon Emissions

- non-coop no dmg
- non-coop
- coop no dmg
- coop
CO₂ Mitigation: C.E. Analysis
Mitigation Target: 450 and 550 ppmv
Mitigation Target: 450 and 550 ppmv

World Industrial Carbon Emissions (GtC)

- BAU
- 450
- 550
Energy and Carbon Intensities

Trajectories in the energy intensity/carbon intensity
wrt 2002

Reduction in Energy Intensity wrt 2002

Reduction in Carbon Intensity wrt 2002

-10% 0% 20% 40% 60% 80% 100%

0% 20% 40% 60% 80% 100%

450 550 BAU
Wind & Solar electricity

TWh

- 60% load factor
- 30% load factor

Renewables: role of load factor
CCS: quantities

Carbon sequestred

GtC

- 550
- 450
- BAU
CCS: effect of capture rate in a 450ppmv
CCS: effect of leakage rate in a 450ppmv

Carbon sequestred

GtC

0.0%
0.1%
0.3%
0.5%

2002 2012 2022 2032 2042 2052 2062 2072 2082 2092 2102
Endogenous Technical Change

LbD: Investment cost of wind&solar plants wrt to BAU

Energy R&D investments
Policy Costs
Costs and procrastination

Costs of procrastination: 3% discounted

-0.03% 0.4% 0.2%
0% 4% 3.5%
1% 2% 5%
2% 3% 7.6%
3% 4% 8%
4% 5% 7.6%
5% 6% 4.2%
6% 7% 8%
7% 8% 7.6%
8% 7.6%

20 yrs on 550 20 yrs on BAU start now
Policy costs: “where” issue

Regional Policy Costs

NPV GDP loss (%)
-25.0% -20.0% -15.0% -10.0% -5.0% 0.0% 5.0% 10.0% 15.0% 20.0%

USA OLDEURO NEUEURO KOSAU CAJAZ TE MENA SSA SASA CHINA EASIA LACA

Fondazione Eni Enrico Mattei
Forestry in a 550ppmv

» halves 550ppmv policy costs
» achieves 50ppmv extra at no cost
» delay energy abatement

Uncertain concentration targets

- **no constr**
- **550**
- **550 determ**
- **450**

**GtC**

**Years:** 2002, 2012, 2022, 2032, 2042, 2052, 2062, 2072, 2082
Conclusions

Optimal abatement (CBA)
- Coop CBA implies lower emissions (600 ppmv at 2100).
- Non-cooperative CBA does not suggest emission levels that scientists might like, mainly because of “global externality” nature of problem.
- Real issue is countries free-riding and how to induce cooperation

Stabilization Policies (C.E.)
- 550 “cheap” target, 450 tougher (real climate damages, tech. evolution)
- Power sector can do the job but needs Nuclear, CCS and Renewables
- Forestry important mitigation option with a bearing on carbon market/energy abat
- 550 no regret option, 20 yrs on BAU 450 is gone
- Climate uncertainties: more intermediate mitigation/interim conc. targets
massimo.tavoni@feem.it

www.feem-web.it/WITCH
C-E Analysis World GWP loss

Discounted Policy Cost
Policy Cost

0.2% NPV GWP loss
-0.01% NPV Consumpt. loss
Distinguishing Features

- Focus on energy sector
Algorithm

Start

Nash Main Source

Regional Subroutines

Initialize variables

Compute global variables

Regional Optimization s.t. global and regional equations

Check decision variables’ deviation from previous iteration value < ε

NO

Yes

Nash Solution

To ease solution searching problem. Each region’s problem solved assuming no interactions

To compute Temp, price of resources, W&S capacity installed necessary in each regional optimization problem

∀ n ∈ N

The algorithm does not handle global constraints.
Forestry

Investigating the role of forestry as a stabilization option

Motivating Issue:
Missing analysis of carbon market response to forestry mgmt

General idea:
Coupling WITCH with a forestry model (Brent Sohngen, Ohio State Univ.)

Carbon prices (to 2150)

WITCH

Forestry

Carbon sequestred per year, per region
Forestry Results

Forestry relevant abatement option: 1/3 of total abatement to 2050, 1.5GtC/yr, smaller in share afterwards.

Avoided deforestation most determinant to 2050, afforestation kept for later (when higher carbon prices).

Significant reductions in policy costs.

However, delayed abatement in clean energy and E.T.C.: implication if revised climate targets.

Cumulative Carbon Abatement

LbD: Investment cost of wind&solar plants wrt to BAU

Other abatement
Forestry: NON-OECD
Forestry: OECD

Other abatement
Forestry: NON-OECD
Forestry: OECD
Applications so far

• Cost-Benefit Analysis
• Cost-effectiveness Analysis of climate policies
• Linking Forestry Management to Climate Change Policy
• Role of Uncertainty in Technological Change Processes
• Energy Technology Spillovers
• Role of Free Riding
• Role of Discounting
Investigating uncertain effectiveness of innovation in backstop technology

Motivating Issues:
Literature concentrates on uncertainty of climate damages and costs
1. Some preliminary research on uncertain future arrival of a backstop technology
2. Just few studies (Baker et al. 2006) on uncertain effectiveness of R&D

General idea:
Develop a stochastic version of WITCH and analyze the effect of uncertainty on:
» optimal levels of investment in R&D fostering the arrival of a carbon-free backstop technology
» the costs of a stringent climate policy
Uncertainty Results

- Numerical results confirm analytical findings: modeling innovation in a backstop tech. as an uncertain process leads to lower estimates for mitigation costs and higher optimal level of R&D investments.

- Energy sector is a rigid system, costs will strongly depend on the feasibility of other carbon-free technologies (CCS, nuclear).

- Entry time of backstop technology affects optimal levels of R&D investments.
Future Applications

• Interactions between energy markets and climate policy
• Uncertainty of climate damages
• Spillovers and uncertain technological breakthroughs
• Linking land use management-forestry-energy and climate policy
• CDM and embodied technological spillover
• Accounting for non-cooperative behaviors in choosing the optimal climate policy instrument under uncertainty
• Mitigation vs Adaptation strategies


www.feem-web.it/witch
CO2, energy and income

![Graph showing CO2 emissions per capita vs energy per capita for various regions like USA, OLDEURO, NEWEURO, KOSAU, CAJANZ, MENA, SSA, SASIA, CHINA, LA&CA. Each region is represented by a differently colored circle.](Image)
TOP DOWN
- DICE (Nordhaus) and Entice-BR (Popp) no energy detail nor regional disaggregation.
- DEMETER (Gerlagh), no regional disaggregation nor strategic choice of optimal investment profiles.

BOTTOM UP
- Energy system models (e.g., Markal, Message), no forward looking nor accounting for strategic behavior and related inefficiencies.

HYBRID MODELS SOFT LINKED
- MERGE (Richels et al.) stand-alone optimization nor accounting for strategic behavior and related inefficiencies.

HYBRID MODELS HARD LINKED
- MIND (Edenhofer et al.) no regional disaggregation nor strategic choice of optimal investment profiles. Single fuel.
- **WITCH** (World Induced Technical Change Hybrid model)
The Objective Function

For each region \((n)\) forward-looking central planner maximizes present value of \((\log)\) per capita consumption (5-yr time steps):

\[
W(n) = \sum_{t} L(n,t) \{ \log[c(n,t)] \} R(t)
\]

choosing the optimal path of investment variables simultaneously and strategically with respect to the other decision makers.

Consumption of the single final good obeys to the economy budget constraint:

\[
C(n,t) = Y(n,t) - I_C(n,t) - \sum_{j} I_{R&D,j}(n,t) - \sum_{j} I_{j}(n,t) - \sum_{j} O&M_j(n,t)
\]

\[
- \sum_{f} P_f(n,t) X_f(n,t) - P_{CCS}(n,t) CCS(n,t)
\]

- Final Good
- Energy R&Ds
- Electricity Generation
- Operation & Maintainance

Net fuel expenditures
CCS (Transport and storage costs)
Gross output produced via capital, labour (=population) and energy services.

\[ Y(n,t) = \frac{\text{TFP}(n,t) \left[ \alpha(n) \cdot \left( K_C^{1-\beta(n)}(n,t) L^{\beta(n)}(n,t) \right)^\rho + (1 - \alpha(n)) \cdot ES(n,t)^\rho \right]^{1/\rho}}{\Omega(n,t)} \]
The Energy Sector

The Objective Function
ETC is represented through both *accumulation of experience* and *R&D investment*:

i. **Learning by Doing** via experience curves in power plants investment cost

\[ SC_j(n,t) = B_j \sum K_j(n,t-1)^{-\log_2 PR_j} + \xi_n \]

world learning, assume technology spillover

ii. **Energy R&D** for increasing *energy efficiency* (Popp)

\[ ES(n,t) = \left[ \alpha_H HE(n,t)\rho + \alpha_{EN} EN(n,t)\rho \right]^{1/\rho} \]

\[ HE(n,t+1) = aI_{R&D}(n,t)^b HE(n,t)^c + HE(n,t)(1 - \delta_{R&D}) \]
PROMOTION STRATEGIES FOR ELECTRICITY FROM RENEWABLES IN THE EU – LESSONS LEARNED

Reinhard Haas

Energy Economics Group, Vienna University of Technology

ROSKILDE, 22nd May 2007
SURVEY

1. Introduction
2. Additional costs for final customers
3. A comparison of the success
4. Achievements and prospects
5. The issue of competition
6. Conclusions

Thanks to the EC (DG RESEARCH, DG TREN)
1 INTRODUCTION

CORE MOTIVATION:

Policy targets for an INCREASE of RES-E!

(e.g. currently discussed targets of 20% for 2020)
### Survey on Instruments to Promote Electricity from Renewables

#### What is the problem?

<table>
<thead>
<tr>
<th>Capacity-driven strategies</th>
<th>REGULATORY</th>
<th>VOLUNTARY</th>
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<tbody>
<tr>
<td>Generation-based</td>
<td>- RPS</td>
<td>- National generation targets</td>
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<td>- Quota-based TGCs</td>
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<td>Investment focused</td>
<td>- Bidding/Tendering</td>
<td>- National installation or capacity targets</td>
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<td>- feed-in tariffs,</td>
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<td>- rate-based incentives</td>
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<td>- Net metering</td>
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<td>Price-driven strategies</td>
<td>- Rebates</td>
<td>- Green Power Marketing</td>
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<td>Generation-based</td>
<td>- Soft loans</td>
<td>- Green tariffs</td>
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<td>- Tax incentives</td>
<td>- Solar stock exchange</td>
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<td>Investment focused</td>
<td>- Rebates</td>
<td>- Contracting</td>
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<td>- Soft loans</td>
<td>- Shareholder progr.</td>
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<td>- Tax incentives</td>
<td>- Contribution</td>
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<td>Other</td>
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<td>- Bidding</td>
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<td>- NGO-marketing</td>
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<td>- Selling green buildings</td>
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<td>- Retailer progr.</td>
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<td></td>
<td></td>
<td>- Financing</td>
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<td></td>
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<td>- Public building prog.</td>
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</table>
What is the problem?
Which instrument fits best?

Answer depends on POLICY OBJECTIVE

- Should RES-E technologies be promoted on broad scale?
- Should an ambitious RES-E target be met in the short and long-term?
- Should RES-E technologies be promoted on broad scale?
- Should it reflect the external costs?
- Should it be compatible with the conventional electricity market?
- How should the premium costs / burden for consumer be distributed over time?
- Is international burden sharing for consumer an important goal?
- Should the system be implemented on a national or international level?

Source: GREEN-X
INTRODUCTION

MAJOR PROBLEM:

Correct design of policy

• with respect to:
  • renewable targets
  • Financial incentives
  • Credibility for investors
  • Consideration of external costs?
All regulatory promotion schemes (Quota-based TGC systems, tendering systems, Feed-in tariffs) create an artificial market and cause transfer costs (additional costs)
It is important to minimize these additional transfer costs. Why?

These additional costs have finally to be paid by the electricity customers (regardless which promotion scheme is chosen)
Method of approach
(EU-project GREEN-X)

STATIC COST RESOURCE CURVES

EURO/kWh

predicted

Uncertainty

more expensive capacities

cheapest capacities

kWh

Potential of RES
Method of approach
(EU-project GREEN-X)

Minimise additional costs for consumers = Producer Surplus + Generation costs - Revenues electricity market

( - Avoided External costs)

Price, costs [Euro/MWh]

$P_{MC}$

Price of certificate

$P_{ele}$

Producer surplus (PS)

Avoided External costs

Generation Costs (GC)

Quota Q

Quantity kWh

$MC$ ... marginal generation costs

$P_{ele}$ ... market price for (conventional) electricity

$P_{MC}$ ... Marginal price for green electricity (due to quota obligation)
Transfer costs vs avoided costs

Example: Promotion of wind in Germany 2005

Source: Krewitt/Schlomann: Externe Kosten ...(2006)
The lower the additional costs (=transfer costs) are which have finally to be paid by electricity customers, the higher will be public acceptance. The larger will be the amount of additional electricity generated from RES.
An example from the conventional electricity market:

in several countries (e.g. Germany, Belgium) customers are fed up with the high profits the large incumbent utilities make in the “free” market they request a re-regulation of electricity prices!
3. REQUIREMENTS TO SUCCESSFUL STRATEGIES

Major objectives:

• increase the amount of electricity from renewables and
• reduce costs!
Effectiveness vs Costs

Feed-in tariffs (2000-2004)

Tradable certificates

IT  BE  UK  AT  DE  ES  SE

Costs (c/kWh)

kWh/cap/yr
SUCCESS CRITERIA FOR FIT’s

1. Use a stepped FIT and calculate starting values carefully

2. Identify ecological bonus

3. Decrease over time, link to conv. electr. market prices
CONSIDER DYNAMICS OF PRICES AND COSTS:

- For FIT/premium: Consider „learning“ by a dynamic component!
SUCCESS CRITERIA FOR QUOTA-BASED TGC’s

1. Penalty >> MC

2. Ensure long-term planning horizon!

3. Focus on new plants

4. Allow banking
MAJOR PITFALLS FOR QUOTA-BASED TGC’s

1 Market to small: e.g. in a small country for one technology with very limited potential -> Non-Liquid because every single plant is known (e.g. Flanders (BE))

2 Penalty is too low (e.g. UK)

3 Short planning horizon (e.g. UK 2003, Italy)

4 The problem of windfall profits for (existing) capacities (e.g. Flanders (BE), Sweden)
4. WHAT HAS BEEN ACHIEVED SO FAR AND WHAT CAN BE EXPECTED FOR THE FUTURE?
TOTAL ELECTRICITY GENERATION FROM RENEWABLES IN EUROPE

- 1997: 12.9%
- 2005: 13.6%
ELECTRICITY GENERATION FROM „NEW“ RENEWABLES IN EUROPE

1997: 1.4%

2005: 4.5%

- Biogas
- Solid biomass
- Biowaste
- Geothermal electricity
- Photovoltaics
- Wind on-shore
- Wind off-shore
SOME RESULTS OF GREEN-X: CASE STUDY 2020

Total current electricity consumption: 3200 TWh

Investigated cases:

**NO HARMONISATION**
- Business-as-usual (BAU)
  - Continuation of current national policies up to 2020
- Improved national policies
  - Efficient & effective national policies
- Technology-specific support
  - Feed-in tariffs - harmonised

**HARMONISATION IN 2015**
- Non technology-specific support
  - Quota obligation based on TGCs - harmonised

**BAU**
- Historical development
- Indicative RES-E Target (2010)
- Introduction of harmonised policies (2015)
- BAU-forecast
- Strengthened national policies
- Technology-specific harmonised FIT scheme
- Non technology-specific harmonised TGC system

- 1156 TWh (improved national & harmonised policies)
- 951 TWh (BAU)
Total electricity generation from RES (EU25) as share of gross electricity demand

BAU scenario ... how far will we come with current RES policies?

... the impact of an active DSM policy and conventional energy prices
5. COMPETITION?

• conventional electricity market: To maximize profits utilities merge to avoid competition

• hard to imagine that a European-wide TGC market will work disconnected from these large incumbents

• TGC markets: Why should competition work if it does not in the conventional electricity market?

• Utilities/generators are in favour of TGC because they can make much more money and control the market, the construction of new plants much better
6. CONCLUSIONS (1)

• We are far away from an optimal solution but we are on the way!
• Careful design of strategies: by far the most important success criteria!
• There should be a clear focus on NEW capacities!
• To ensure significant RES-E deployment in the long-term, it is essential to promote a broad portfolio of different technologies
• Ensure credibility of the system! Avoid „stop-and-go“ approaches
6. CONCLUSIONS (2)

- Currently, a well-designed (dynamic) FIT system provides a certain deployment of RES-e fastest

- Instead of harmonisation: Stimulate/Foster competition between promotion schemes/between countries: Which system/where provides new RES-E with highest benefits for society?

- IMPROVE THE CURRENT SYSTEMS!

  e.g. Feed-in-cooperation DE and ES -> why not a “Club” of TGC – countries (learning from SE)?
In the long run?

- Re-regulation?
- Priority production from renewables should persist
- Ecological bonus of the magnitude of external cost relief could prevail “eternally” (at least as long as no environmental taxes are introduced)
- However, for sustainable policy -> parallel focus on demand-side conservation of high priority!
INTERESTED IN FURTHER INFORMATION?

- Download reports from:
  www.eeg.tuwien.ac.at
  www.green-x.at
  www.optres.fhg.de

- E-Mail to:
  Reinhard.Haas@tuwien.ac.at
The cost of the cellulosic biofuels, $P_{ADV\text{BIO}}(n,t)$, is modeled as decreasing with investments in dedicated R&D through a power formulation:

$$P_{ADV\text{BIO}}(n,t) = P_{ADV\text{BIO}}(n,0) \cdot (TOT_{R&D,ADV\text{BIO}}(n,t))^{-\eta}$$

where $\eta$ for the relationship between new knowledge and cost and $LAG=2$

$$TOT_{R&D,ADV\text{BIO}}(n,t) = \sum_n K_{R&D,ADV\text{BIO}}(n,t - LAG) + \sum_{\tau=t-1}^{t} I_{R&D,ADV\text{BIO}}(n,\tau)$$

Spillovers: different assumptions on completeness of spillovers (through lag time)
Perspectives of the IDA Energy Year 2006 project

Per Nørgård
Risø DTU, Denmark

Henrik Lund and Brian Vad Mathiesen
Aalborg University, Denmark
The Danish Society of Engineers’ Energy Plan 2030
IDA Energy Year 2006 project

A one-year process
- Involving 1600 professionals

2 conferences
- Jan 2006: Opening
- Dec 2006: Concluding

40 workshops
- knowledge workshops
- vision workshops
- roadmap workshops

Energy technologies in 2030
- performance
- price

7 themes:
- Buildings
- Transport
- Wind, sun & waves
- Fuel cells, hydrogen, bio & batteries
- Oil & gas
- Industrial processes
- Energy systems
IDA objectives

by year 2030

- environment
to reduce the CO2-emission by 50%
- energy
to maintain the security of energy supply
- business
to increase the technology export by 200%
Danish Board of Technology – Energy Combi Scenario

Savings  Combi  Energy+

Wind  Bio

Reference scenario

DK Energy Strategy 2025

• by The Danish Energy Authority, for The Danish Ministry of Transport and Energy, 2005
• IDA: 2025 -> 2030
Reference - DK energy projections
Reference - DK oil and gas
EnergyPLAN simulation

EnergyPLAN characteristics:
• Time series analysis on hourly basis
• All energy exchange in one node
• Links between energy sectors
• Include energy storage

EnergyPLAN simulations include:
• Heat buffer capacity in district heating systems
• Conversion from electricity to heat by heat pumps
• Electricity buffering by electrical cars
## Measures

### Buildings
- Energy for space heating: -50% relative to Ref 2030
- Solar heating: 30% of heating
- Electricity consumption: -50% relative to Ref 2030

### Industry
- Fuel consumption: -40% relative to Ref 2030
- Electricity consumption: -30% relative to Ref 2030
- Industrial CHP: +20% electricity
- Biofuels: +80 PJ
Measures

Wind, sun, wave
- Wind: +3000 MW
- Wave: 5% of electricity in 2030
- Photovoltaic: 2% of electricity in 2030

Oil & gas
- North Sea: -45 % CO2 emission
Measures

Transport

• Stabilising the total person-transport work
• Air traffic: 50% -> 30% increase (2005 – 2030)
• 20% transport work from road to rail and ship
• Energy efficiency: +30%
• Biofuels in 2030: 20%
• Electricity in 2030: 20%

Biomass

• In 2030: 30% of primary
Results - Primary energy supply

The chart shows the primary energy supply in Peta Joule (PJ) for the years 2004, Ref. 2030, and IDA 2030. The chart compares the energy sources such as Export, RE electricity, Solar thermal, Biomass, Natural gas, Oil, and Coal.

Results - CO2 emissions

Results - Business potential

Export in billion DKK per year

- Energy-efficient renovation
- Biofuels
- Bioethanol
- Heat pumps
- Fuel cells
- Wave power
- Solar thermal
- Photovoltaics
- Management and measuring
- Electricity, oil and gas management
- Wind power
- District heating and CHP

2004

IDA 2030

Results - Economic costs

![Graph showing economic costs of CO₂, fuel, operation and maintenance, and investments for Ref. 2030 and IDA 2030. The graph is labeled with Million DKK per year, ranging from 0 to 100,000 in increments of 20,000. The bars represent CO₂ costs, fuel, operation and maintenance, and investments.]
Sensitivity analysis

Fluctuating oil prices  +50% investment costs  6% interest rate
Conclusion

The actual figures indicate:

- Energy: -40 %
  - Ref 2030: 1000 PJ
  - IDA 2030: 600 PJ
- CO2 emission: -60 %
  - 1990: 50 mio ton
  - IDA 2030: 20 mio ton
- Fossil fuels: -65 %
  - Ref 2030: 800 PJ
  - IDA 2030: 300 PJ
- Technology export: +500 %
  - DKK 30 billion @ 2005
  - DKK 160 billion @ 2030
- Costs: -20 %
  - Ref 2030: DKK 80 billion
  - IDA 2030: DKK 65 billion

It is both technical possible and economic feasible at the same time in 2030 to achieve:

- less total energy consumption,
- less total CO2-emission,
- less fossil fuels consumption and
- increased technology export
- even at reduced economic costs.

Sustainable solution can only be achieved through:

- Energy conservation
- Energy efficiency
- System solutions
- Flexibility
- Couplings between energy sectors
<table>
<thead>
<tr>
<th>Elbesparelse i husholdningen</th>
<th>Dansk Referene 2030</th>
<th>Ingeniørforeningens energiplan 2030</th>
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</thead>
<tbody>
<tr>
<td>Rumvarmebesp. i fjernvarmeområdet</td>
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<td>Rumvarmebesp. uden for fjernvarmeomr.</td>
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<td>Solvarme, små individuelle</td>
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<td>Solvarme, store i fjernvarmeområder</td>
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<td>Elbesparelse i industrien</td>
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<td>Brændselsbesparelse i industrien</td>
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<td>Biomasse i industrien</td>
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<td>Effektiviseringer på Nordsøen</td>
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<td>Nulvækst i persontransport</td>
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<td>Mindre vækst i luffarten</td>
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<td>Kollektiv trafik</td>
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<td>Elbiler</td>
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<td>Effektiv vejtransport</td>
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<td>Bioethanol i vejtransport</td>
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<td>Mikro brændselscelle kraftvarme</td>
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<td>Fjernvarmeudvidelse</td>
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<tr>
<td>Store brændselscelle kraftvarme</td>
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<tr>
<td>Vindkraft</td>
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<td>Bølgekraft</td>
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<td>Solceller</td>
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<tr>
<td>Varmepumper i fjernvarmeområder</td>
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<tr>
<td>Fleksibelt elforbrug</td>
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</table>

| -1,000 | -500 | 0 | 500 | 1,000 | 1,500 | 2,000 | 2,500 | 3,000 | 3,500 | 4,000 |
Example: The IBUS bio-refinery concept

1 t Wheat straw

Hydrothermal pretreatment
80°C

160-200°C

190-230°C

Water
4 t

14.6 GJ

Chopping

0.65 GJ

Power

4 GJ

Heat

Surplus

Power Plant

PP1

PP2

PP3

SSF

450 kg
C5-molasses

Bioethanol (99% konc.)
180 litre (2800 km)

6.6 GJ

Solid Biofuel
Lignin: 356 kg

3.7 GJ

6.6 GJ

Energy efficiency: 76 %

Fossil fuel substitution: 11 GJ

* Production of heat and power: 0,65/0,45+4/1,66

Some of challenging discussions at IDA workshops

Buildings
• New building energy standards – but 70 % of the buildings in DK in 2030 are from before today
• District heating infrastructure in the future?

Biomass feedstock is a limited resource
• CO2-reduction: CHP
• Independency of oil: transport
• Business: bio fuels technologies
• Biomass for energy -> increased food prices

Transport sector
• Energy efficient technologies are present – but are not introduced!
• -10 % person road transport -> +50 % rail transport
• Energy and CO2 related to international transport not included!
• International person transport: alternatives to fly?
IDA recommendations (€ 1.5 billion / year)

- The existing agreement on **energy savings** should be extended and continued (1.7% annual reductions in energy consumption).
- An **industry energy savings fund** should be established (€ 100 mio annually).
- A **heat conservation fund** should be established (€ 100 mio annually).
- € 30 billion should be invested in the Danish **rail road system** over the next 30 years.
- The Danish national funds for **research, development and demonstration** should be increased to € 100 mio annually.

- **Innovation markets** for renewable energy technologies should be established by quotas in order to accelerate the development.
- All costs – including **externalities** – should be included in the market prices.
- **Popular engagement** in energy savings and renewable technologies should be supported.
- **CO2 quotas** should be sold through biddings.
- A thorough service control of all **energy taxes** and tariffs should be made.
- **100% renewable energy cities** should be established in Denmark.

Follow-up


National Rail Authority
Thanks

per.norgaard@risoe.dk

http://ida.dk/Netvaerk/Energiaar+2006
Integrated European Energy RTD as part of the innovation chain to enhance renewable energy market breakthrough

Professor Peter Lund
Helsinki University of Technology, Finland
peter.lund@tkk.fi

Risö International Energy Conference 2007
22-24 May 2007
Observations from the past on market penetration of new energy technologies

- It may take decades to reach a noteworthy share on world markets
- The public support required to bring a new major energy source into world-scale may be some hundred billion dollars in total

Table. Estimated public support to selected technologies in billion $ (2003 prices).

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<tr>
<td>PV</td>
<td>0</td>
<td>10.6</td>
<td>8.3</td>
<td>19.2</td>
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<tr>
<td>Solar th.</td>
<td>0</td>
<td>10.3</td>
<td>3.4</td>
<td>13.7</td>
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<tr>
<td>Wind</td>
<td>0</td>
<td>49.1</td>
<td>4.2</td>
<td>53.3</td>
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<tr>
<td>Nuclear</td>
<td>176.6</td>
<td>0</td>
<td>157</td>
<td>333.6</td>
</tr>
</tbody>
</table>

Figure. Penetration of selected energy technologies (MW).
Public and private support to energy technology R&D has dropped dramatically

- Public energy R&D support of Member States is < 1/3 of the 1980's level; renewables only a small share
- Energy companies invest «0.5% of turnover in R&D
- Energy in EU's 7th FP is <15% of the budget; 20 years ago it was 50%
- EU’s Advisory Group on Energy (FP6) advised a 4x increase in energy R&D funding

Source: European Commission, IEA
**European Strategic Energy Technology Plan**

- “The European Strategic Energy Technology Plan (SET-Plan) calls for a more integrated approach to match the most appropriate set of policy instruments to the needs of different technologies at different stages of the development and deployment cycle”. [An Energy Policy for Europe, European Commission, 10 Jan. 2007]

- Key objectives for energy technology: 1) to lower the cost of clean energy, 2) to put EU industry at forefront of low carbon technology

A vision to match the long term challenge competitively

<table>
<thead>
<tr>
<th>Technology</th>
<th>2020</th>
<th>2030</th>
<th>2050</th>
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<tbody>
<tr>
<td>Energy efficiency</td>
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<tr>
<td>Biofuels (2nd generation)</td>
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<td>Large-scale offshore &amp; European supergrid</td>
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<tr>
<td>Photovoltaics</td>
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<tr>
<td>Fuel cells and hydrogen</td>
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<tr>
<td>Sustainable coal and gas (CCS)</td>
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<tr>
<td>4th gen. fission and fusion</td>
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<td><strong>20% renewable target</strong></td>
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<tr>
<td><strong>20% energy reduction target</strong></td>
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</table>
Outline of the presentation

- **Starting point**: Advisory Group of Energy’s recommendations and concerns on energy R&D from 2006 and the EU’s Energy Policy Communication from 2007

- **Aim**: Investigating future market breakthrough of renewable energy technologies (€ and yrs); key parameter is cost-effectiveness

- **Scope**: matching policy measures (technology, market support) with specific technology needs over the whole innovation process

- **Approach**: modeling the commercialization process with links to policy measures
Three important elements/aspects in an integrated RTD strategy

1. Commercialization process of new innovations or improvements of energy technologies
   - precedes the more massive market penetration and is very development intensive and needs strong public support

2. Technology diffusion process
   - describes the market share of the new technology over time once the ‘take-off’ has occurred after market introduction and the new technology is becoming competitive against the prevailing ones;

3. Policies and instruments
   - enhance above processes to enable full commercial market breakthrough
   - includes also the overall policy needed to master the whole commercialization process.
Commercialization process

- The commercialization process involves several stages (non-linear)
- Several endogenous and exogenous factors affect breakthrough
- Distance from market
  - Incremental improvements for existing products << radical innovations without established markets
Technology diffusion

- Boundary between commercialization process and market penetration often overlapping
- Penetration described by diffusion (speed of penetration, inertia)

A: introduction
B: lock-in
C: growth
D: saturation

Energy impact or market volume

R&D

Public support or learning investments

time
Policy instruments in an integrated strategy

- Here policy instruments consider the whole commercialization process and aim at a full market breakthrough
- Technology push and market pull measures are interlinked and considered in parallel
- Catalyzing measures to boost the commercialization
  - market forces and mechanisms (close cooperation between the different market players

Examples of different profiles of the innovation chain. R=research, D$_1$=development, D$_2$=demonstration (pilot production), D$_3$=dissemination, D$_4$=deployment

Combined diffusion and learning model

- The tool combines price-conditioned and segmented technology diffusion with an endogenous learning model.
- Three interlinked submodels: 1) calculation of the production cost of energy ($C$), 2) estimation of the market volume increase ($dV_t$) and 3) cost reduction ($dC_V$).
- The speed of market penetration is described by a diffusion model.
- Cost reductions are described by endogenous learning, i.e. learning by doing and by using and economies of scale.

$$C = \text{annualized cost of investment} + \text{O&M} + \text{fuel} + \left[ \text{risk premiums} \right] + \left[ \text{public subsidy} \right] + \left[ \text{system integration cost} \right] + \left[ \text{CO2 cost} \right] \div \text{annually produced energy}$$

Market penetration occurs if $C \leq \text{reference cost of energy}$

$$\frac{dV_t}{dt} = \beta \cdot \frac{V_t}{V_\infty} \cdot (V_\infty - V_t) \rightarrow V_t = V_0 + \sum_t dV_t$$

$$dC_V = -C_V \cdot \frac{\ln 2}{\ln P} \cdot \frac{dV_t}{V_t}$$
Linking policies and strategies to the model

- Policy measures improve the economic competitiveness of the new technologies (C) and influence the penetration rate ($\beta$) which leads to increased volume ($V$)

- Examples on how policies (both RTD and market deployment) may influence the costs of the new technology (a-f)
  - a: classical learning curve
  - b: strong R&D effort
  - c: too high subsidies, low competition, bottlenecks
  - d: c+ measures
  - e: demand>>supply, oversidized
  - f: e+ measures
Examples of the use of the model

- **Case: Photovoltaics - effects of a major R&D effort**
  - PV is marginal but growing fast, 2-4 x more expensive than consumer electricity
  - Base case: feed-in-tariffs are used to ensure competitiveness; Hypothesis: a concerted RTD initiative (JTI) could be justified; a 30% cost reduction possible in 10 years through stronger R&D

- **Case: Wind - impact of possible market disturbance**
  - Wind >1% of world electricity and fast growing, marginally more expensive
  - Base case: feed-in-tariffs are used to ensure competitiveness; Hypothesis: 1) demand for wind >> supply and could cause a short market disturbance, i.e. for 2 years costs a) stagnate and b) +5%yr 2) in large investments the cost of capital becomes important
Case PV: penetration results

- PV ~ 1% of world electricity at t=30 yrs or around 400 TWh
- PV becomes fully competitive at t=20 yrs in consumer segments in EU
PV (2): effects of technology jump

- The concerted R&D strategy case could save 150 billion € in investment costs and 33 billion € of public support in investments over the next 30 years.

![Graph showing subsidy and investment over time with different cases indicated.](image-url)
Case wind: penetration results

- Wind 10% of world electricity at t=30 yrs; 20% in EU
- The cost of wind-electricity is halved in 30 years
- Cost-effective (non-subsidized) penetration starts at t=10 years in EU-onshore and t=20 yrs in EU-offshore segments
- Market saturation in some segments
Wind (2): effects of disturbances

- A market disturbance of 2 years could mean 100 billion € extra investment cost over 30 years; 30 billion € (learning stagnation) - 37 billion € (cost disturbance) more public subsidies

- Advantageous loans could lower the public support needed by 85% and save 70 billion € in the base case
Observations and conclusions (1)

1. Distance from the cost breakeven point affects the optimal balance between technology push and market pull actions
   – if far away from the commercial breakthrough, focused R&D efforts to enable technology jumps could be more effective than market deployment
   – in case of PV the economic benefits from a strong joint European R&D initiative would be highly motivated

2. When reaching higher volumes and exercising strong market pull measures to accelerate market growth even short disturbances in technology cost trends may turn out be costly
   – careful planning of the subsidy levels to balance possible supply/demand bottlenecks is stressed
   – in case of wind a planning of joint European policies could be highly motivated
Observations and conclusions (2)

3. Full commercialization of new energy technologies needs patient and continuous public support
   - A long time horizon is most likely necessary (10-20 years), public support should be viewed as an investment with long pay-off
   - Several factors may change the total financial support needed
   - Involving European financing bodies in the investments could enable cheaper capital costs

Illustration of the pay-back of public support for PV over 50 years
Impacts of high energy prices on long-term energy-economic scenarios for Germany

Volker Krey, Dag Martinsen, Peter Markewitz
Research Centre Jülich, Institute of Energy Research - Systems Analysis and Technology Evaluation (IEF-STE), Jülich, Germany

Manfred Horn
DIW Berlin, Berlin, Germany

Felix Chr. Matthes, Verena Graichen, Ralph O. Harthan, Julia Repenning
Öko-Institut, Berlin, Germany
Motivation

• „new“ energy price levels since 2004
• energy-economic scenarios do/did not cover price levels
• compilation of adapted scenarios
• analysis of impacts:
  – supply structures
  – competitiveness of energy-saving measures
  – resulting CO$_2$-emissions
Energy Price Scenarios

Reference Scenario

- oil price 2030: 37 US$\textsubscript{2000}/barrel
- Source: EWI/Prognos 2006
Energy Price Scenarios

High Price Scenario

oil price 2030: 82 US$/2000/barrel

Source: EIA 2006
Energy Price Scenarios

Price Spike Scenario

oil price 2010: 105 US$2000/barrel
Source: Goldman Sachs 2005

- crude oil
- LPG
- gasoline
- light fuel oil
- heavy fuel oil
- natural gas
- natural gas
- hard coal
Analysis

• Energy Systems Model (IKARUS-LP):
  – consistent scenarios
  – impacts on whole energy system
    (supply and end-use sectors)

• Electricity Sector Model (ELIAS):
  – detailed analysis of electricity generation
  – interaction with carbon emissions trading
Modeling Approach

- **Perfect-Foresight**
  - t<sub>0</sub> t<sub>1</sub> t<sub>2</sub> ... t<sub>N</sub>

- **Time-Step (myopic)**
  - t<sub>0</sub> t<sub>1</sub> t<sub>2</sub> ... t<sub>N</sub>

- Optimum

- Price shock e.g. energy consumption

- t<sub>0</sub> t<sub>1</sub> t<sub>2</sub> ... t<sub>N</sub>
Total Primary Energy Supply

Reference Scenario

- Nuclear
- Renewables
- Gas
- Oil
- Others
- Lignite
- Hard coal
- Total

PJ
High Price Scenario

Total Primary Energy Supply

- Nuclear
- Renewables
- Gas
- Oil
- Others
- Lignite
- Hard coal
- Total

Pj


-7%
-30%
-11%
0%
+7%
$x2.4$
Total Primary Energy Supply

Price Spike Scenario

- Nuclear
- Renewables
- Gas
- Oil
- Others
- Lignite
- Hard coal
- Total

- 2%
- 7%
- 3%
- 1,3
- 7%
- 23%
- 15%
- 18%
+ 4%
0%
+ 4%
- 2%
- 7%

PJ
CO₂-Emissions
High Price Scenario

cumulative -6.6%, 1340 Mt

-11% -83 Mt
-9% -16 Mt
-19% -19 Mt
-10% -34 Mt

Transport
Residence
Commercial
Industry
Other Conversion
Power & Heat Generation
Total
**CO₂-Emissions**

Price Spike Scenario

cumulative -8.4%, 1690 Mt

<table>
<thead>
<tr>
<th>Year</th>
<th>Transport</th>
<th>Residence</th>
<th>Commercial</th>
<th>Industry</th>
<th>Other Conversion</th>
<th>Power &amp; Heat Generation</th>
<th>Total</th>
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<tbody>
<tr>
<td>2000</td>
<td></td>
<td>-13% -28 Mt</td>
<td></td>
<td>-25 Mt</td>
<td>-9% -15 Mt</td>
<td>-12% -39 Mt</td>
<td>-8.4%, 1690 Mt</td>
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<tr>
<td>2005</td>
<td>107 Mt</td>
<td></td>
<td></td>
<td>0% 0 Mt</td>
<td>-1% -1 Mt</td>
<td>-1% 5 Mt</td>
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</tr>
<tr>
<td>2010</td>
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<td>-14% -28 Mt</td>
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<td>-25 Mt</td>
<td>-9% -15 Mt</td>
<td>-12% -39 Mt</td>
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<tr>
<td>2015</td>
<td></td>
<td></td>
<td>-21% -25 Mt</td>
<td>-17 Mt</td>
<td>-17 Mt</td>
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<tr>
<td>2020</td>
<td></td>
<td></td>
<td></td>
<td>-17 Mt</td>
<td>-17 Mt</td>
<td>-17 Mt</td>
<td></td>
</tr>
<tr>
<td>2025</td>
<td></td>
<td></td>
<td></td>
<td>-1% -1 Mt</td>
<td>-1% -1 Mt</td>
<td>-1% 5 Mt</td>
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<tr>
<td>2030</td>
<td></td>
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<td></td>
<td>-1% -1 Mt</td>
<td>-1% -1 Mt</td>
<td>-1% 5 Mt</td>
<td></td>
</tr>
</tbody>
</table>
Final Energy Consumption

Reference Scenario

- Transport
- Residence
- Commercial
- Industry
- Total
Final Energy Consumption
High Price Scenario

Institute of Energy Research – Systems Analysis and Technology Evaluation (IEF-STE)
Final Energy Consumption
Price Spike Scenario

Institute of Energy Research – Systems Analysis and Technology Evaluation (IEF-STE)
ELIAS Model Approach

• investments in power generation sector
• utility perspective
• political instruments:
  – taxes
  – feed-in-tariffs for renewables (EEG)
  – promotion of CHP (KWKG)
  – emissions trading scheme/allocation rules
ELIAS Model Approach

User settings

Technology data, cost data, economic background data, political interventions

Investment analysis

Power demand, technical lifetime, fuzzy function

Unit cost of electricity

Decision on power plant construction

Technology mix

Evaluation
Electricity Sector – Current Allocation

- Nuclear Energy
- Lignite
- Hard Coal
- Natural Gas
- Renewables
- Others
- CO2

Historical value, Reference Scenario, 2010, 2020, 2030, High Price Scenario

TWh

Mio. t CO₂
Electricity Sector – Full Auctioning

- Nuclear Energy
- Lignite
- Hard Coal
- Natural Gas
- Renewables
- Others
- CO2

Historical value
Reference Scenario
High Price Scenario
Conclusions

• energy-savings in end-use sectors but: relaxation effects in some sectors
• increased utilization of renewables
• electricity generation: natural gas vs. coal (strongly dependent on energy price levels and allocation rules)
• domestic hard coal competitive coal-to-liquids: > 55 US$/barrel
Thank You!
Polygeneration

Thomas Rostrup-Nielsen
HALDOR TOPSOE A/S
Haldor Topsøe A/S - Risø – May 23 2007
Outline

- IGCC and Polygeneration
- TIGAS – Topsoe’s Integrated Gasoline Synthesis
- Integration of IGCC & TIGAS
  - Process performance
  - Economics
  - Options for CO₂ abatement
• IGCC and Polygeneration
• TIGAS – Topsoe’s Integrated Gasoline Synthesis
• Integration of IGCC & TIGAS
  – Process performance
  – Economics
  – Options for CO2 abatement
Inflation Adjusted Monthly CRUDE OIL PRICES (1946- Present)
In May 2006 Dollars
© www.InflationData.com
Updated 7/18/06

Dec. 1979 Monthly Ave. Peak
$100.52 in June 2006 Dollars

Nominal Peak $38 (Mo. Ave. Price)
Intraday Prices peaked much higher

June 2006 Monthly Ave.
Oil Price $62.85

Nominal Monthly Ave. Oil Price
Inflation Adjusted Monthly Average Oil Price

Source of Data:
Illinois Basin Crude Prices- www.ioga.com/Special/crudeoil_Hist.htm
CPI-U Inflation index- www.bls.gov
Coal as a Raw Material

- High oil prices & Security of supply
- Interesting to generate power from coal
  - if capable of dealing with CO₂
- Interesting to generate chemicals otherwise obtained from oil from coal
  - E.g. transportations fuels
- Interesting to use technology which can utilize renewable energy sources
  - E.g. biomass
IGCC Plant

Dirty synthesis gas
CO + H₂ + CO₂

Clean synthesis gas
CO + H₂ + CO₂
Ideal for chemicals production

Coal
Residue
Biomass
Waste

Gasification ➔ Gas Cleaning ➔ Combined Cycle ➔ Power

Oxygen
Possible to remove CO₂ here
IGCC & Chemicals Production
Polygeneration

Coal
Residue
Biomass
Waste

Gasification

Gas Cleaning

Combined Cycle

Fuel
Steam

Chemicals synthesis

Power

Methanol
DME
Gasoline etc.
• IGCC and Polygeneration
• TIGAS – Topsoe’s Integrated Gasoline Synthesis
• Integration of IGCC & TIGAS
  – Process performance
  – Economics
  – Options for CO2 abatement
Worlds first Gas to Gasoline Plant – New Zealand – 1986

Gasoline synthesis

MeOH synthesis

Classic MTG process

Synthesis gas → Module adjustment → Sour gas removal → Comp. → Methanol Synthesis → Raw Methanol day tank

CO2

Methanol DME Equilibrium → Gasoline synthesis → Product separation

Off-gases → Light ends → Gasoline → Water

Gasoline

Haldor Topsøe A/S - Risø – May 23 2007

MeOH synthesis

Gasoline synthesis
1980’s Demonstrations from Natural Gas

Houston – 1 ton/day

Frederikssund – few kg/day
• IGCC and Polygeneration
• TIGAS – Topsoe’s Integrated Gasoline Synthesis
• Integration of IGCC & TIGAS
  – Process performance
  – Economics
  – Options for CO₂ abatement
IGCC & TIGAS

Coal Residue Biomass Waste → Gasification → Gas Cleaning → Combined Cycle → Power

Fuel

Steam

Methanol DME synthesis → Gasoline synthesis → Product separation

LPG Gasoline Water

Gas feed to TIGAS % 100% 25%

Power MW 1103 524 957

Gasoline ton/h 0 60 15

LPG MW 0 105 26

Total MW 1103 1352 1164

Gasoline yield, %

25% to TIGAS

100% to TIGAS

DME Equilibrium Temperature, °C

- Risø – May 23 2007
Efficiency

Combined IGCC & Gasoline

Stand alone Gasoline Plant

IGCC

I1  I2  I3  I4
Economics

- Gasoline value, 2 $/Gal
- Integration schemes

- TIGAS: favorable
- Polygeneration: favorable
- IGCC: favorable

- Equal product value accounting for production efficiencies

- Export Electricity value, c/kWh
- Power value, c/kWh
- Gasoline value, $/gal
- Product value, Mio $/y
How good an Investment?
Assumed investment for TIGAS add-on 10,000 USD/bbl/d

Pay-Back time - Sensitivity to Gasoline & Power value
Case C4 - 60 t/h Gasoline + 525 kW Power

Pay back time, years

Export Electricity value, c/kWh

1.00 $/gal
1.25 $/gal
1.50 $/gal
1.75 $/gal
2.00 $/gal

Operational flexibility
Operational Flexibility

![Diagram showing operational flexibility](image)

**Equal product value accounting for production efficiencies**

- **TIGAS** favorable
- **Polygeneration** favorable
- **IGCC** favorable

### Pay back time

<table>
<thead>
<tr>
<th></th>
<th>IGCC</th>
<th>I4</th>
<th>I4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gas feed to TIGAS %</td>
<td></td>
<td>100%</td>
<td>25%</td>
</tr>
<tr>
<td>Power MW</td>
<td>1103</td>
<td>524</td>
<td>957</td>
</tr>
<tr>
<td>Gasoline ton/h</td>
<td>0</td>
<td>60</td>
<td>15</td>
</tr>
</tbody>
</table>

**Pay back time**

<table>
<thead>
<tr>
<th></th>
<th>$/gal</th>
<th>IGCC</th>
<th>I4</th>
<th>I4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gasoline value</td>
<td>1.3</td>
<td></td>
<td></td>
<td>2.0</td>
</tr>
<tr>
<td>Max gasoline years</td>
<td>5.4</td>
<td></td>
<td>0.83</td>
<td></td>
</tr>
<tr>
<td>Operational flex. years</td>
<td>2.5</td>
<td></td>
<td>0.79</td>
<td></td>
</tr>
</tbody>
</table>

Haldor Topsøe A/S - Risø – May 23 2007
PSO Project

- Project to demonstrate renewable technology for generation of Power and Gasoline
  - HTAS, DONG, Novozymes
  - Gasoline Pilot in connection with existing gasification plant
CO₂ abatement

- Power & Gasoline with CO₂ sequestration
Conclusions

• Topsøe’s TIGAS process is suitable for polygenration integrated with an IGCC plant
  – Based on coal, waste, biomass

• Fast pay-back times are achieved for the TIGAS unit given realistic power and gasoline values

• Operational flexibility offers improved economics

• Topsøe is preparing to demonstrate an improved TIGAS process through a Danish government sponsored PSO project
Sustainable bioethanol production combining biorefinery principles and intercropping strategies

Mette Hedegaard Thomsen
Henrik Hauggaard-Nielsen
Anneli Petersson
Anne Belinda Thomsen
Erik Steen Jensen
Bioethanol

1. generation Bioethanol:

Substrate: Sugar (sucrose) from sugarcane and starch from corn or wheat.

No chemical/physical pretreatment of biomass before enzymatic hydrolysis.

Optimised, commercial enzymes available

2. generation Bioethanol:

Substrate: Lignocellulosic materials (straw, corn stover, wood, waste)

Chemical/physical pretreatment necessary to facilitate enzymatic hydrolysis.

Expensive, non-commercial enzymes
2. generation Bioethanol production

Pretreatment

Hemicellulose → Enzymes → Hydrolysis

Cellulose → Enzymes → Hydrolysis

Lignin

Enzymes

Mikroorganisme

C5

Fermentation

C6

Fermentation

Distillation

Bio-Ethanol
Pre-treatment method most suitable for annual crops such as wheat straw and corn stover.

**Exothermic reaction:**
- High temperature
- High pressure
- Oxygen
- Reaction time 10-15 min.

\[-R- + O_2 \rightarrow \text{Products} + \text{CO}_2 + \text{H}_2\text{O} + \text{Energy}\]

Auto hydrolysis of hemicellulose sugars from the solid fraction because of production of carboxylic acids.
Choice of biomass resources

Source: http://dataservice.eea.europa.eu
Choice of crop species and energy consumption

Source: Source ITCF- UNIP (1999)

Energy consumption (MJ/ha)

Atm. N₂-fixation

N fertilizer
Seed
Herbicides
P fertilizer
Mechanisation
Criteria to include when producing biomass

- no effect on food production;
- no increase in pressure on biodiversity;
- no increase in environmental pressure;
- no ploughing of previously unploughed permanent grassland;
- a shift towards more environmentally friendly farming
  - agroforestry – local integration and adoption of wood resources
  - perennial energy crops
  - environmental sensitive areas – e.g. groundwater protection

Source: http://ec.europa.eu/energy/res/biomass_action_plan

It is required to design new cropping methods and multifunctional cropping systems when addressing a "new" issue - energy.
- low-input systems (energy and pesticides)
- harvest, storage and transportation
- Win-win solutions energy, environment, and recreation
Intercropping as an alternative cropping strategy

• Intercropping is defined as the growing of two or more crops in the same piece of land and on the same time - planned crop diversity
  • Associated *interspecies interactions* are tools for:
    • improved utilization of resources (light, water nutrients),
    • increased yield stability,
    • control of nutritional quality of grains
    • managing weeds, pest and diseases in *low-input systems*

• **LEES NEED FOR **PERSTICIDES AND FERTILIZERS!!!
Complementary use of resources

- Complementarity is implemented in the crop stand when species utilize resources differently

![Graph showing resource availability over time or space for Species A, B, and C]
A mix of white clover (*Trifolium repens* L.) and ryegrass (*Lolium perenne* L.) are important in many agroecosystems today:

1. high quality feed for livestock

2. high productivity (>10 t ha⁻¹ yr⁻¹) in unfertilized pastures, with 95% of the N from N₂ fixing clover (Høgh-Jensen and Schjørring, 1994)

3. their roots and stubble contain 60-110 kg N ha⁻¹ (Hauggaard-Nielsen et al., 1998) reducing N requirements for succeeding crops

4. integration of pastures diversify the traditional cereal rich rotations

5. fields with clover grass pastures can be harvested several times a year and the green biomass can be collected and processed to ethanol throughout the year.
Clover grass as raw material for bioethanol production

- Rich in carbohydrates:
  cellulose and hemicellulose
- Rich in minerals, especially nitrogen ↓
  nutrients for yeast in fermentation

Question:
Can the sugars in clover grass be converted to ethanol after pretreatment and enzymatic hydrolysis ?????
<table>
<thead>
<tr>
<th>Biomass</th>
<th>Cellulose (g/100 g DM)</th>
<th>Hemicellulose (g/100 g DM)</th>
<th>Ligning (g/100 g DM)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wheat straw</td>
<td>33.9</td>
<td>23.0</td>
<td>19.1</td>
</tr>
<tr>
<td>Clover</td>
<td>16.6</td>
<td>10.5</td>
<td>14.4</td>
</tr>
<tr>
<td>Grass</td>
<td>23.9</td>
<td>17.5</td>
<td>12.8</td>
</tr>
</tbody>
</table>
High mineral content ⇒ sufficient nutrients for microbial fermentation ⇒ less fossil energy input in ethanol process
Pretreatment conditions

- Clover-grass mixture (1:1) were cultivated in the experimental fields of Risø National Laboratory, Denmark.

- Samples of pure clover and grass - and 1:3 clover-grass mixture - was separated by hand.

- The samples were dried at 50°C to constant weight and milled to a size of less than 2 mm prior to pretreatment and further analysis.

- Wet oxidations were performed in the loop autoclave using 6% dry matter (DM) at different process parameters. The pretreated biomass was filtrated into a fiber fraction and a liquid fraction.

<table>
<thead>
<tr>
<th>Material</th>
<th>Temp. (°C)</th>
<th>Time (min)</th>
<th>O₂ (bar)</th>
<th>Na₂CO₃ (g/l)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clover</td>
<td>195</td>
<td>10</td>
<td>12</td>
<td>2</td>
</tr>
<tr>
<td>Grass</td>
<td>195</td>
<td>10</td>
<td>12</td>
<td>2</td>
</tr>
<tr>
<td>CL-G (1:1)</td>
<td>175</td>
<td>10</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>CL-G (1:1)</td>
<td>175</td>
<td>10</td>
<td>12</td>
<td>2</td>
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<tr>
<td>CL-G (1:1)</td>
<td>185</td>
<td>10</td>
<td>3</td>
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<tr>
<td>CL-G (1:1)</td>
<td>185</td>
<td>10</td>
<td>12</td>
<td>2</td>
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<tr>
<td>CL-G (1:1)</td>
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<td>3</td>
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</tr>
<tr>
<td>CL-G (1:1)</td>
<td>195</td>
<td>10</td>
<td>12</td>
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</tr>
<tr>
<td>CL-G (1:3)</td>
<td>195</td>
<td>10</td>
<td>3</td>
<td>2</td>
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</tbody>
</table>
Pretreatment Yields

<table>
<thead>
<tr>
<th>Material/Pretreatment conditions</th>
<th>Yield (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glucose 195°C 10 min 12 bar 2 g/l</td>
<td>100</td>
</tr>
<tr>
<td>Xylose 195°C 10 min 12 bar 2 g/l</td>
<td>100</td>
</tr>
<tr>
<td>Glucose 195°C 10 min 3 bar 2 g/l</td>
<td>100</td>
</tr>
<tr>
<td>Xylose 195°C 10 min 3 bar 2 g/l</td>
<td>100</td>
</tr>
<tr>
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</tr>
<tr>
<td>Xylose 195°C 10 min 12 bar 2 g/l</td>
<td>100</td>
</tr>
</tbody>
</table>

Material/Pretreatment conditions

- Glucose
- Xylose
Fermentation of pretreated clover grass with *Mucor indicus*

**Graph:**
- **X-axis:** Time (h)
- **Y-axis:** Concentration (g/l)
- **Legend:**
  - Glucose
  - Xylose
  - Ethanol

**Legend:**
- **Aerobic:** Glucose concentration decreases, Xylose and Ethanol concentrations remain low.
- **Oxygen limited:** Glucose concentration decreases significantly, Xylose concentration increases, Ethanol concentration remains low.
Yeast fermentation of fresh clover grass

Fructans are polymeric carbohydrates consisting of variable numbers of fructose molecules with terminal sucrose.

Grass and clover contain significant amounts of fructans:
Grass: 166 g/kg DM
Clover: 111 g/kg DM

Plant fructan hydrolases are active at pH 4.5 - 5.5 and temp. 25 - 40°C ⇒ Activity during yeast fermentation at 32°C and pH 4-6.
Biorefinery concept

- Clover/grass field
- Wheat field
- Field with intercropping
- Starch for food and industry
- Atm. N₂

- Fresh clover/grass
- Dry straw
- Dry straw and clover/grass

- Pressing of clover/grass
- Pressed clover/grass fibers

- Pretreatment of fibers
- Pretreated material

- Storage and buffer tanks

- Ethanol fermentation
- Distillation
- CO₂

Recirculation of residue and CO₂ back to the fields

- High value/protein rich feed product
- Fertiliser rich in micro and macro nutrients
Theoretical ethanol production

The highest sugar yields were obtained with clover grass pretreated at 195°C for 10 min. using 12 bar O₂ and no Na₂CO₃.

Y<sub>cellulose</sub> = 94 %
Y<sub>hemicellulose</sub> = 66 %

203 kg cellulose/ton DM clover grass ⇒ 107 kg ethanol/ton DM
140 kg hemicellulose/ton DM clover grass ⇒ 63.5 kg ethanol/ton DM
138 kg fructan/ton DM clover grass ⇒ ~ 70.6 kg ethanol/ton DM (depending on yield)

Total: 241 kg ethanol/ton DM ~ 2.4 ton EtOH/ha

Wheat straw: ~ 250 kg ethanol/ton DM ~ 1.25 ton/ha (IBUS treatment)

Clover grass pasture undersown in wheat ~ 964 + 125 kg EtOH/ha = 2.2 ton/ha + grain for feed
Conclusions

• Starch is an important food source, lignocellulose should be the primary raw material for bio-fuel production

• Biomass for bioethanol production should be cultivated using the lowest possible input of fossil energy

• This can be archived by novel cropping strategies like intercropping combining crop species for food/feed and energy

• Clover grass is a promising raw material for bioethanol production e.g. in combination with wheat straw (Thorsted et al. 2006)

• The sugar yields after WO of clover grass were: \( Y_{\text{cellulose}} = 94 \% \), \( Y_{\text{hemicellulose}} = 66 \% \) - giving a theoretical ethanol production of 241 kg/ton DM

• All sugars in alternative raw materials like clover grass can be utilised by using the right biorefinery concept
Biomass for energy is considered a key diversification strategy to improve energy supply security and mitigate GHG emissions. However, bioenergy systems are relatively complex, intersectoral and sitespecific. Therefore, solving problems is challenging and requires synergic contribution of various contributors from the agriculture, forestry, energy industry and environmental sectors to elucidate the most promising pathway for development.

Are we able to create such interdesicipinary collaborations?
Thank you for your attention!
Pretreatment of clover grass

Carbohydrate composition of fiber fraction

Material/Pretreatment conditions

Concentration (g/100g DM)

Glucan

Hemicellulose

Lignin

Cl

G

Cl-G

1:1

175°C

10 min

12 bar

2 g/l

Cl-G

1:1

185°C

10 min

3 bar

2 g/l

Cl-G

1:1

195°C

10 min

12 bar

2 g/l
Pretreatment of clover grass

Carbohydrate composition of liquid fraction

Material/Pretreatment conditions

- Glucose
- Xylose
- Arabinose
- Total hemicellulose
Co-ordination of Renewable Energy Support Schemes in the EU

Poul Erik Morthorst and Stine Grenaa Jensen
Risø National Laboratory
The Technical University of Denmark
Focus on Renewable Energy technologies

• EU suggests binding targets
  • Greenhouse gases has to be reduced by 20% compared to 1990
  • Renewable energy has to cover 20% of gross energy consumption by 2020 – wind power is expected to have a significant role
  • The existing target for renewable technologies was 12% by 2010 – a share of 8% is expected to be achieved by 2010.

• Burden sharing is to be negotiated

• Ambitious?
  • Anyhow, it is binding
What happens in Denmark?
Constant Energy Consumption in spite of strong growth in GDP
Strong Increase in Renewables

Wind Power - Capacity and Share of Domestic Electricity Supply

- Wind Power Capacity [MW]
- Wind Power - Share of Domestic Electricity Supply
Strong Increase in Renewables

Wind Power covered approx. 44% of Power consumption in January in Western Denmark
Strong Increase in Renewables

Wind Power covered approx. 44% of Power consumption in January in Western Denmark.
The New Energy Plan

• Renewables to cover 30% of Gross Energy Consumption in 2025
  • The share is approx. 15% today

• Energy conservation and development of new Energy Technologies

• Wind Power could cover 50% of Danish Power Consumption in 2025
The New Energy Plan

- Renewables to cover 30% of Gross Energy Consumption in 2025
  - The share is approx. 15% today

- Energy conservation and development of new Energy Technologies

- Wind Power could cover 50% of Danish Power Consumption in 2025
Support Systems in EU
Support Systems in EU

- Feed-in Co-operation including Germany and Spain
- Common Green certificate market including Sweden and Norway
  - Did not come true!!
Future Support Systems and the Internal Market in EU

- **With regard to RES-E, what do we want to achieve in the EU?**
  - An economic and resource efficient siting of renewables
  - A replacement of the most inefficient power plants
  - A reduction of CO₂-emissions achieved in the most effective and cheapest way

- **Coordination and regionalization**
  - The way forward for RES-E support in the EU

- **Interactions of Power markets and RES support schemes**
  - How can we get the most efficient transition to a coordinated RES-E development in EU?
Ways to Go – The almost Ideal Case

- Regional power market and regional support system

<table>
<thead>
<tr>
<th>RES-E Support Scheme</th>
<th>Power Market</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>National</td>
<td>Regional</td>
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<tr>
<td>National</td>
<td>Case A</td>
<td>Case B</td>
</tr>
<tr>
<td>Regional</td>
<td>Case C</td>
<td>Case D</td>
</tr>
</tbody>
</table>
Country A – high wind and efficient system

Country B – low wind and inefficient system

Common Power Market
TGC - Almost Ideal Case

• Renewables are sited in the most efficient way
  • Only the wind regime matters

• Consequences for the Power Market
  • The most inefficient plants will be replaced by renewables
  • The more different the two countries are the more beneficial will a common TGC-system be
  • Effective reduction of CO₂, but where the reduction takes place (country A or B) will depend on the marginal conditions at the power market
  • Burden sharing of regulation costs is a problem

• Comparison to a Feed-in tariff
  • The burden sharing is implicitly given by the TGC-quotas in each country – thus there is no need for a common fund as will be the case in a feed-in system
Ways to Go – The troublesome Case

- National Power market and regional support system

<table>
<thead>
<tr>
<th>RES-E Support Scheme</th>
<th>Power Market</th>
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<tbody>
<tr>
<td>National</td>
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<td>Case A</td>
<td>Case B</td>
</tr>
<tr>
<td>Case C</td>
<td>Case D</td>
</tr>
</tbody>
</table>
Country A – high wind and efficient system

Country B – low wind and inefficient system

Tradable Green Certificates - The Troublesome Case

Power Price
TGC-price
Price wind power
Wind Deployment
Consumer Price
Regulation costs

A
B

Separate Power Markets
Consequences for renewables and the Power Market

- Renewables will be sited the most *economic* efficient places, but not the sites with the highest resources.
- Renewables will not replace the most inefficient power plants.
- CO$_2$-reduction in the region will not be efficient implying higher prices for CO$_2$-allowances.
- Burden sharing of regulation costs is also a problem in this case.

The Green Certificates system *is economically optimal at the given market conditions* ..... but

- **Short term solution** - *If we want to move towards a common power market, a common TGC system does bias both the development of renewables and the conventional power system.*
Conclusions

• A common and efficiently working power market is a prerequisite for an efficient common support system
  • Separate power markets might bias the development of the conventional power system

• But other barriers exist as well
  • Lack of competition (monopolies), weak interconnectors…

• The way forward
  • Co-ordination of support schemes
  • Regionalization
Bioethanol
Second generation Bio-fuel – close to commercialisation

Charles Nielsen
DONG Energy
IBUS (Integrated Biomass Utilisation System)

Inbicon A/S (new name for Elsam Biosystems A/S)
Integrated Biomass Conversion

Founded 2003 by
Elsam A/S (now DONG Energy A/S) and
Holm Christensen Biosystemer ApS

for commercialisation of the IBUS concept
Content

- IBUS technology
- Demonstration
- Commercialisation
The IBUS concept

1. Integrated utilisation of sugar/starch and lignocellulosic feedstocks

- Most crops comprises both sugar or starch and lignocellulose
- Lower cost from field to plant
- More biomass can be collected within a given area
- Substantial process synergies
2. Integrated production of bioethanol and electricity

- Electricity generation looses 55-65 % of the input energy as heat
- Ethanol fermentation looses only 3-5 % of the input energy as heat, but requires a lot of process heat
- The huge loss of heat energy from the global electricity generation can be used to cover the demand for heat energy of the future fuel ethanol production

Co-production is the solution
The IBUS concept

Surplus steam

High quality solid biofuel

Fossil fuels

Power Plant

Power Steam

Biofuels

Biomass Plant

Feed

Bioethanol

Fibre

Fertiliser

Straw
Grain
Whole grain crops
Molasses
Bagasse
Sugar cane
Sweet sorghum
Household waste
The IBUS concept

Integration 1. and 2.nd generation technology

Integration with electricity generation and utilization of surplus heat
The IBUS process

- Continued pretreatment
- High dry matter content
- High energy efficiency
- No ligning separation
- Recycling of plant nutrients (nitrogen, phosphor, potassium, and micro minerals)
- Integrated water utilization – no waste water
IBUS results based on wheat straw

Hydro-thermal Pretreatment
Wheat Straw
1 t/h (86% DM)

Water or Condensate
4 ton/h

Fibre Fraction (25-30% DM)
(hemicellulose, cellulose and lignin)

Enzymatic Treatment
Cellulases
Fibre Mash
Yeast

C5 Molasses
447 kg/h (70% DM)
3.9 t/h Condensate

Recycling
(xylose, enzymes)

Ethanol Recovery
Vacuum Stripper
Bioethanol
148 kg/h

C6 Fermentation
Fibre Beer (app. 6 w/w% EtOH.)

Biofuel
(lignin)
315 kg/h

Fibre Stillage
Stillage Separation
Fibre Thin Stillage

Evaporation
Pretreatment

Chopped wheat straw

Pretreated wheat straw
IBUS pretreatment removes lignin as nano-particles

Cellulose microfibrils: 10 – 30 nanometer
Lignin particles: 30 – 40 nanometer

Photo: Royal Veterinary and Agricultural University
Enzymatic liquifaction with high dry matter content

5 Chamber Liquification Reactor
Liquifaction with high dry matter content and fermentation (26% DM)

Ethanol concentration:
- 63 g/kg incl. suspended material
- 83 g/l in the liquid fraction (excl. suspended material)
- 105 ml/l (10.5 vol%) in liquid fraction (excl. suspended material)
Next step output from the IBUS process
Actual energy balance (state-of-the-art)

1 t Wheat straw

Chopping

Hydrothermal pretreatment
80°C
160-200°C
190-230°C

Water
4 t

Solid Biofuel
Lignin: 356 kg

Bioethanol (99% konc.)

180 litre (2800 km)

450 kg
C5-molasses

Power Plant

Surplus

14.6 GJ

Power

Heat

PP1
PP2
PP3

14.6 GJ

0.65 GJ

4 GJ

6.6 GJ

3.7 GJ

Solid Biofuel
Lignin: 356 kg

4.4 GJ

Bioethanol (99% konc.)

180 litre (2800 km)

Energy efficiency: 76 %

Fossil fuel substitution: 11 GJ

* Production of heat and power: 0.65/0.45+4/1.66

Inbi con

Risø • Maj 2007
Main results from the EU project: Co-production of Biofuels

- The IBUS pretreatment can work at high gravity without chemicals
- Fast (5-10 hours), high gravity (30-40 % d.m.) liquefaction at low enzyme concentration (3-4 FPU/g)
- Effective high gravity fermentation (SSF) of more than 80% of cellulose to ethanol by yeast
- Yeast fermentation can be carried out in the presence of lignin
- See more at www.bioethanol.info
IBUS – Low energy cost

- Low price, 4 bar steam from electricity generation
- High gravity processing reduces steam consumption
- Novel particle generation system saves 50-75% electricity compared to traditional hammer milling
- Novel distillation system energized by heat pumps or 1-2 bar steam, is expected to reduce costs with 50% compared with traditional systems
- Drying with superheated steam at 3-5 bar generates steam for multistage evaporation recovering about 90% of drying energy
- The lignin fraction can cover the process energy required for conversion of the straw and a similar quantity of grain
IBUS – long term sustainability

• Use of low pressure steam from electricity generation means energy without CO2 emission
• Recycling of plant nutrients (nitrogen, phosphorus, potassium and microminerals)
• Recycling of process water and condensates means no waste water
• Drying with superheated steam means no VOC emission
IBUS – best basis for biorefineries
Stepwise implementation of biorefineries

1. Sugar/starch feedstocks → IBUS pretreatment → Liquefaction → SSF yeast → Product recovery → Ethanol, DDGS

2. Lignocellulosic feedstocks → IBUS pretreatment → Liquefaction → SSF yeast → Product recovery → Ethanol, C5 molasses, Lignin fraction

3. Lignocellulosic feedstocks → IBUS Ethanol pretreatment → Separation → Fibre fraction → Product recovery → Cellulose fibre → C5 molasses, Lignin

Liquid fraction → Ethanol → Product recovery
# IBUS – R & D

<table>
<thead>
<tr>
<th>Scale</th>
<th>Process</th>
<th>Organization</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Lab scale</strong></td>
<td>Pretreatment</td>
<td>Risoe National Laboratory</td>
</tr>
<tr>
<td>10 kg/h of straw</td>
<td>Hydrolysis and fermentation</td>
<td>The Royal Veterinary and Agricultural University</td>
</tr>
<tr>
<td><strong>Pilot scale</strong></td>
<td>Particle generation, pretreatment, liquefaction, fermentation, product recovery</td>
<td>Dong Energy A/S</td>
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<tr>
<td>100 kg/h of straw</td>
<td></td>
<td></td>
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<tr>
<td><strong>Pilot scale</strong></td>
<td>Particle generation, pretreatment</td>
<td>Dong Energy A/S</td>
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<tr>
<td>1000 kg/h of straw</td>
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<tr>
<td><strong>Process Innovation</strong></td>
<td>From field to fuel</td>
<td>Holm Christensen Biosystemer ApS</td>
</tr>
<tr>
<td><strong>Demonstration plant</strong></td>
<td>Fully integrated IBUS plant located at one of Dong Energy’s Power Plants (Kalundborg) Planned start of production: ultimo 2009</td>
<td>Inbicon A/S</td>
</tr>
<tr>
<td>4 t/h of straw d.m. + 4 t/h of grain d.m.</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Content

- IBUS technology
- Demonstration
- Commercialisation
Feedstock development

- Whole crop development
- Silage handling
- Feedstock improvement
- Other innovative technologies

Common processes

- IBUS Straw
- IBUS Grain

Synergi projects between IBUS straw and IBUS grain

Budget

- Katalytic biogasolin production
- Integration of biogas - production
- Alternative separation technologies
- Alternativ C5 utilization

Demonstration center for related technologies
Demonstration concept
Synergies between straw and grain

Large international potential for technology integrating 1. and 2nd generation ethanol

Examples of synergies at demo-plant:

- DWG as feedstock in the straw process
- Surplus of energy from the straw process goes to the grain process
- Water and energy exchange between the two processes
- Optimization of field to ethanol plant (whole crop handling)
- Compound feed production based on DWG and C5 molasses
- Integration of main processes
- Improvement of feedstocks
- Logistic and marketing
Kalundborgs industrial symbiose

The existing symbiose is extended with biofuel and by-products
Kalundborg
Powerplant, refinery and enzyme producer
Kalundborg
New Synergy

Enzymes from Novozyme

Bioethanol til Statoil
Syngas / H₂ til Statoil

Rawmaterials from and feed to DLG

Proces steam → - 50% C02-emission
Solid biofuel → Substitute coal
Process water to deSOx-plant
District heat to city
Harbor facilities
Content

- IBUS technology
- Demonstration
- Commercialisation
Demo plant

- Goal: Production before UN Copenhagen Clima Summit November 2009

- Capacity: 4 ton straw + 4 ton grain (budget ca. 40 mill US)

- Partners (Inbicon, Dong Energy, Novozymes, Statoil and Danish Farmers COOP)

- Technology: (IBUS technology - integration of 1. and 2. bio ethanol connected to Power Plant)
Commercialization

- Technology company – new investors
- Verification of technology (scale-up, reliability, demonstration of yields, environmental impact and feasibility)
- Partners: (North America, China and Brazil)
- Overseas demonstration projects
- Contracts
Succes criteria

• Best economy
  (energy efficiency, enzymes, capital cost and value of by-products)

• Market share
  (the right partners and fast deployment)
Thank you for your attention
Long-term biofuels scenarios: preliminary results from REFUEL – A European Road Map for Biofuels

Henrik Duer
COWI A/S, Denmark
Contents

1. Introduction

2. REFUEL objectives

3. Resource base assessment

4. Biofuels mix development

5. Barriers identified

6. Conclusions
1. Introduction

Biofuels production in Europe 1991-2005

- Biodiesel: ca 80%
- Bioethanol: ca 20%
- Tot. 2005: Ca 3 Mtoe

Ca 1% of road transport

Source: PREMIA
Development

Now 1st generation in rapid deployment:
• Major investments in biodiesel, bioethanol
• Long-term feedstock availability
• Sustainability, GHG performance?

Future biofuels mix:
• Advanced biofuels (FT-diesel, advanced bioethanol)
• Remaining 1st generation?

Central question: what can we expect from biofuels in the long run?
Technological learning and land scarcity

Feedstock production

- 1st generation crops
- 2nd generation crops

Conversion technology

- 1st generation fuels
- 2nd generation fuels
2. REFUEL, main objectives

To develop an ambitious, yet realistic road map for an effective deployment of biofuels until 2030 in the EU25+

- **The destination:** Ambitious, but realistic biofuels targets
- **The route:** the least-cost biofuel mix and biofuel chains
- **The purpose of the journey:** impact assessments on GHG, SoS, socio-economics, stationary sector, environment
- **At the wheel:** key stakeholders, technological innovation needed, learning, options and barriers
- **Paving the way:** related policies on energy, agri, technology, measures (incentives, obligations)
3. Resource assessment

- Population
- Food use per capita
  - Agricultural prod.
    - Food consumption
    - Livestock intensity
    - Self sufficiency ratio
  - Built +
- Land claim
  - Arable
  - Permanent
  - pasture
- Total land
- Land available for bio-energy crop production

Input variables
Calculated result
Scenario variable
Land suitability to crops

- Priority for food etc.
- Demand scenarios
- Agric. production
- Natura2000
- No drastic land use changes
Some preliminary results: Feedstock

Total land potential if used for perennial grasses:

EU27: 1/10 of prim. energy demand
1/3 of gasoline/diesel demand

EU plus Ukraine: 1/6 of EU 2030 prim. energy demand
Or half of gasoline/diesel demand.

[Charts showing land conversion and feedstock production]
Sensitivities

More conservative:
• More organic farming
• Less rapid productivity developments in CEEC

Ca 10% less land potential

More optimistic:
• GMO’s
• Faster convergence in CEEC

Ca 15% more land potential
Nota bene:
Costs, not prices
4. Biofuel mix assessment

- Least-cost biofuels mix over full chain: Production, transport, conversion, distribution, end-use (*Biotrans* model)
- 1\textsuperscript{st} and 2\textsuperscript{nd} generation biofuels
- Crops, residues etc.
- Within-EU trade, imports
- Key issue: Learning -
  - In feedstock production
  - In conversion
2005 biofuel costs built-up in Biotrans

The diagram illustrates the biofuel costs for different types of biofuels in 2005. The costs are divided into five main categories: End use, Distribution, Transport, Processing, and Waste and residues. The diagram shows the cost distribution for Bio-diesel, Bio-ethanol (1st), Bio-FT-diesel, Bio-DME, Bio-ethanol (2nd), and Bio-SNG.
Preliminary results: Biofuel consumption

25% target (2030) imports allowed

Diesel substitutes dominate
Late intro of 2\textsuperscript{nd} gen.
Brazilian Ethanol
Avg GHG: 25 kg/GJ
Preliminary results: Feedstock base

25% target (2030) imports allowed

- Diesel substitutes dominate
- Late intro of 2\textsuperscript{nd} gen.

- Brazilian Ethanol
Aggregated cost build-up

- Additional end use
- Distribution (excl. transport)
- Transport
- Conversion (incl. import)
- Waste and residuals
- Energy crops
Other scenarios and policy options:

No imports:
- Earlier introduction of 2nd generation (2013)
- Higher average fuel costs until 2025
- Better GHG profile: < 20 g/MJ biofuel

Lower biofuels ambitions (15% in 2030):
- No introduction of 2nd generation
- Lower average fuel costs
- Worse GHG profile: >30 g/MJ

Impact of 2nd generation biofuel obligation by 2020:
- Higher costs in 2015-2025, lower costs afterwards?
- Better GHG performance
Further work

Assessment of biofuel growth limitations
- Adoption rates to new crops
- Competition for ligno feedstock
  - RES-Electricity and Heat production
  - CHP is attractive
  - Assessment of potential and effects in Peep model

Implications of other policies
- Specific targets for diesel and gasoline substitutes?
- Active AGRI policy?
- (internal and external) trade policy?
5. Barriers identified

Basic fact that:
• the process is politically and not market driven

Four key barriers identified by stakeholders:
1. No clear strategy on how to achieve the biofuel targets
2. There is no common market for biofuels
3. There is no common technical standards
4. Limited resources of land

We address issues related
6. Conclusions

- Rapid development of biofuels in EU: need for robust long-term strategy
- Significant land potential available (Central and East)
- Least-cost: 1st general may dominate long
- Policy driven
- For development of best GHG-performing biofuels:
  - Specific incentives needed
  - Adequate incentives and policies will be crucial
Thank you

Further information and updates:

www.refuel.eu

info@refuel.eu

hdu@cowi.dk

londo@ecn.nl
UpWind

A Wind Research Project under the 6th Framework Programme

Program Manager
Peter Hjuler Jensen
RISØ National Laboratory
Technical University of Denmark
Installed Wind Power in the World
- Annual and Cumulative -

Global Wind Power Status
Cumulative MW by end of 2000, 2003 & 2006

# Installed capacity in 2005 and 2006 (Americas)

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<thead>
<tr>
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<tbody>
<tr>
<td>Argentina</td>
<td>1</td>
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<td>31</td>
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<td>Mexico</td>
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<td>USA</td>
<td>2,431</td>
<td>9,181</td>
<td>2,454</td>
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<tr>
<td>Other Americas</td>
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<td>54</td>
<td>2</td>
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<tr>
<td><strong>Total Americas</strong></td>
<td><strong>2,671</strong></td>
<td><strong>10,062</strong></td>
<td><strong>3,515</strong></td>
<td><strong>13,577</strong></td>
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## Installed capacity in 2005 and 2006 (Asia)

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<tr>
<td>P.R. China</td>
<td>498</td>
<td>1,264</td>
<td>1,334</td>
<td>2,588</td>
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<tr>
<td>India</td>
<td>1,388</td>
<td>4,388</td>
<td>1,840</td>
<td>6,228</td>
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<tr>
<td>Taiwan</td>
<td>60</td>
<td>72</td>
<td>46</td>
<td>118</td>
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<tr>
<td>Rest of Asia: Indonesia, N. Korea, Malaysia, Philippines, Thailand, Vietnam, etc.</td>
<td>25</td>
<td>28</td>
<td>0.0</td>
<td>28</td>
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<tr>
<td><strong>Total South &amp; East Asia</strong></td>
<td><strong>1,971</strong></td>
<td><strong>5,753</strong></td>
<td><strong>3,220</strong></td>
<td><strong>8,963</strong></td>
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</table>

*Source: BTM Consult ApS - March 2007*
**Installed capacity in 2005 and 2006 (Europe)**

<table>
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<td>Norway</td>
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<tr>
<td>Poland</td>
<td>10</td>
<td>65</td>
<td>105</td>
<td>170</td>
</tr>
<tr>
<td>Portugal</td>
<td>502</td>
<td>1,087</td>
<td>629</td>
<td>1,716</td>
</tr>
<tr>
<td>Spain</td>
<td>1,764</td>
<td>10,027</td>
<td>1,587</td>
<td>11,614</td>
</tr>
<tr>
<td>Sweden</td>
<td>76</td>
<td>554</td>
<td>62</td>
<td>571</td>
</tr>
<tr>
<td>Switzerland</td>
<td>3</td>
<td>11</td>
<td>0</td>
<td>11</td>
</tr>
<tr>
<td>Turkey</td>
<td>0</td>
<td>20</td>
<td>56</td>
<td>76</td>
</tr>
<tr>
<td>UK</td>
<td>447</td>
<td>1,336</td>
<td>631</td>
<td>1,967</td>
</tr>
<tr>
<td>Rest of Europe: Other East European and Baltic countries.</td>
<td>57</td>
<td>132.1</td>
<td>130.6</td>
<td>262.7</td>
</tr>
</tbody>
</table>

**Total Europe**

<table>
<thead>
<tr>
<th>Total Installed MW 2005</th>
<th>Total Accu. MW 2005</th>
<th>Total Installed MW 2006</th>
<th>Total Accu. MW 2006</th>
</tr>
</thead>
<tbody>
<tr>
<td>6,372</td>
<td>41,044</td>
<td>7,682</td>
<td>48,627</td>
</tr>
</tbody>
</table>

*Source: BTM Consult ApS - March 2007*
## Installed capacity in 2005 and 2006 (Rest of World)

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Australia</td>
<td>296</td>
<td>717</td>
<td>79</td>
<td>796</td>
</tr>
<tr>
<td>Japan</td>
<td>168</td>
<td>1,159</td>
<td>298</td>
<td>1,457</td>
</tr>
<tr>
<td>New Zealand</td>
<td>0</td>
<td>167</td>
<td>3</td>
<td>170</td>
</tr>
<tr>
<td>Pacific Islands</td>
<td>0</td>
<td>5</td>
<td>6</td>
<td>11</td>
</tr>
<tr>
<td>South Korea</td>
<td>20</td>
<td>89</td>
<td>106</td>
<td>194</td>
</tr>
<tr>
<td><strong>Total OECD-Pacific</strong></td>
<td><strong>484</strong></td>
<td><strong>2,137</strong></td>
<td><strong>491</strong></td>
<td><strong>2,628</strong></td>
</tr>
<tr>
<td>Egypt</td>
<td>34</td>
<td>180</td>
<td>51</td>
<td>231</td>
</tr>
<tr>
<td>Morocco</td>
<td>10</td>
<td>64</td>
<td>58</td>
<td>122</td>
</tr>
<tr>
<td>Tunisia</td>
<td>0</td>
<td>28</td>
<td>0</td>
<td>28</td>
</tr>
<tr>
<td>Rest of Africa: Algeria, Cape Verde, Ethiopia, Libya, South Africa, etc.</td>
<td>0</td>
<td>6</td>
<td>0</td>
<td>6</td>
</tr>
<tr>
<td><strong>Total Africa</strong></td>
<td><strong>44</strong></td>
<td><strong>278</strong></td>
<td><strong>109</strong></td>
<td><strong>386</strong></td>
</tr>
<tr>
<td>Middle East: Jordan, Iran, Iraq, Israel, Saudi Arabia, Syria, etc. (excl. Egypt)</td>
<td>0</td>
<td>101</td>
<td>0</td>
<td>101</td>
</tr>
<tr>
<td>Transition Economies: incl. Russia, White Russia, Ukraine, Uzbekistan, Kazakhstan, etc.</td>
<td>0</td>
<td>23.7</td>
<td>0.0</td>
<td>23.7</td>
</tr>
<tr>
<td><strong>Total other continents and areas:</strong></td>
<td><strong>0</strong></td>
<td><strong>124.4</strong></td>
<td><strong>0.0</strong></td>
<td><strong>124.4</strong></td>
</tr>
</tbody>
</table>

*Source: BTM Consult ApS - March 2007*
## Installed offshore wind power in the World

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Denmark</td>
<td>0</td>
<td>397.9</td>
<td>0</td>
<td>397.9</td>
</tr>
<tr>
<td>Ireland</td>
<td>0</td>
<td>25</td>
<td>0</td>
<td>25</td>
</tr>
<tr>
<td>The Netherlands</td>
<td>0</td>
<td>18.8</td>
<td>108</td>
<td>126.8</td>
</tr>
<tr>
<td>Sweden</td>
<td>0</td>
<td>23.3</td>
<td>0</td>
<td>23.3</td>
</tr>
<tr>
<td>UK</td>
<td>90</td>
<td>214</td>
<td>90</td>
<td>304</td>
</tr>
<tr>
<td><strong>Total capacity - World</strong></td>
<td><strong>90</strong></td>
<td><strong>679</strong></td>
<td><strong>198</strong></td>
<td><strong>877</strong></td>
</tr>
</tbody>
</table>

## The 10 largest markets in 2006 (Annual MW)

<table>
<thead>
<tr>
<th>Country</th>
<th>2004</th>
<th>2005</th>
<th>2006</th>
<th>Share %</th>
<th>Cum. Share %</th>
</tr>
</thead>
<tbody>
<tr>
<td>USA</td>
<td>389</td>
<td>2,431</td>
<td>2,454</td>
<td>16.3%</td>
<td>16%</td>
</tr>
<tr>
<td>Germany</td>
<td>2,054</td>
<td>1,808</td>
<td>2,233</td>
<td>14.9%</td>
<td>31%</td>
</tr>
<tr>
<td>India</td>
<td>875</td>
<td>1,388</td>
<td>1,840</td>
<td>12.3%</td>
<td>43%</td>
</tr>
<tr>
<td>Spain</td>
<td>2,064</td>
<td>1,764</td>
<td>1,587</td>
<td>10.6%</td>
<td>54%</td>
</tr>
<tr>
<td>P.R. China</td>
<td>198</td>
<td>498</td>
<td>1,334</td>
<td>8.9%</td>
<td>63%</td>
</tr>
<tr>
<td>France</td>
<td>138</td>
<td>389</td>
<td>810</td>
<td>5.4%</td>
<td>68%</td>
</tr>
<tr>
<td>Canada</td>
<td>123</td>
<td>239</td>
<td>776</td>
<td>5.2%</td>
<td>73%</td>
</tr>
<tr>
<td>UK</td>
<td>253</td>
<td>447</td>
<td>631</td>
<td>4.2%</td>
<td>78%</td>
</tr>
<tr>
<td>Portugal</td>
<td>274</td>
<td>502</td>
<td>629</td>
<td>4.2%</td>
<td>82%</td>
</tr>
<tr>
<td>Italy</td>
<td>357</td>
<td>452</td>
<td>417</td>
<td>2.8%</td>
<td>85%</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>6,725</strong></td>
<td><strong>9,918</strong></td>
<td><strong>12,711</strong></td>
<td><strong>82.5%</strong></td>
<td><strong>85.9%</strong></td>
</tr>
</tbody>
</table>

## Growth rates in the Top-10 markets

<table>
<thead>
<tr>
<th>Country</th>
<th>Accu. end 2003</th>
<th>Accu. end 2004</th>
<th>Accu. end 2005</th>
<th>Accu. end 2006</th>
<th>Growth rate 2005-2006 %</th>
<th>3 years average %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Germany</td>
<td>14,612</td>
<td>16,649</td>
<td>18,445</td>
<td>20,652</td>
<td>12.0%</td>
<td>12.2%</td>
</tr>
<tr>
<td>USA</td>
<td>6,361</td>
<td>6,750</td>
<td>9,181</td>
<td>11,635</td>
<td>26.7%</td>
<td>22.3%</td>
</tr>
<tr>
<td>Spain</td>
<td>6,420</td>
<td>8,263</td>
<td>10,027</td>
<td>11,614</td>
<td>15.8%</td>
<td>21.8%</td>
</tr>
<tr>
<td>India</td>
<td>2,125</td>
<td>3,000</td>
<td>4,388</td>
<td>6,228</td>
<td>41.9%</td>
<td>43.1%</td>
</tr>
<tr>
<td>Denmark</td>
<td>3,076</td>
<td>3,083</td>
<td>3,087</td>
<td>3,101</td>
<td>0.5%</td>
<td>0.3%</td>
</tr>
<tr>
<td>P.R. China</td>
<td>571</td>
<td>769</td>
<td>1,264</td>
<td>2,588</td>
<td>104.7%</td>
<td>65.5%</td>
</tr>
<tr>
<td>Italy</td>
<td>922</td>
<td>1,261</td>
<td>1,713</td>
<td>2,118</td>
<td>23.6%</td>
<td>31.9%</td>
</tr>
<tr>
<td>UK</td>
<td>759</td>
<td>889</td>
<td>1,336</td>
<td>1,967</td>
<td>47.2%</td>
<td>37.3%</td>
</tr>
<tr>
<td>Portugal</td>
<td>311</td>
<td>585</td>
<td>1,087</td>
<td>1,716</td>
<td>57.9%</td>
<td>76.8%</td>
</tr>
<tr>
<td>France</td>
<td>274</td>
<td>386</td>
<td>775</td>
<td>1,585</td>
<td>104.6%</td>
<td>79.4%</td>
</tr>
<tr>
<td><strong>Total &quot;Ten&quot;</strong></td>
<td><strong>35,431</strong></td>
<td><strong>41,634</strong></td>
<td><strong>51,303</strong></td>
<td><strong>63,203</strong></td>
<td><strong>23.2%</strong></td>
<td><strong>21.3%</strong></td>
</tr>
</tbody>
</table>

*Source: BTM Consult ApS - March 2007*
The 10 largest markets by end of 2006 (cumulative MW)

<table>
<thead>
<tr>
<th>Country</th>
<th>2004</th>
<th>2005</th>
<th>2006</th>
<th>Share %</th>
<th>Cum. Share %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Germany</td>
<td>16,649</td>
<td>18,445</td>
<td>20,652</td>
<td>27.8%</td>
<td>28%</td>
</tr>
<tr>
<td>USA</td>
<td>6,750</td>
<td>9,181</td>
<td>11,635</td>
<td>15.7%</td>
<td>43%</td>
</tr>
<tr>
<td>Spain</td>
<td>8,263</td>
<td>10,027</td>
<td>11,614</td>
<td>15.6%</td>
<td>59%</td>
</tr>
<tr>
<td>India</td>
<td>3,000</td>
<td>4,388</td>
<td>6,228</td>
<td>8.4%</td>
<td>67%</td>
</tr>
<tr>
<td>Denmark</td>
<td>3,083</td>
<td>3,087</td>
<td>3,101</td>
<td>4.2%</td>
<td>72%</td>
</tr>
<tr>
<td>P.R. China</td>
<td>769</td>
<td>1,264</td>
<td>2,588</td>
<td>3.5%</td>
<td>75%</td>
</tr>
<tr>
<td>Italy</td>
<td>1,261</td>
<td>1,713</td>
<td>2,118</td>
<td>2.9%</td>
<td>78%</td>
</tr>
<tr>
<td>UK</td>
<td>889</td>
<td>1,336</td>
<td>1,967</td>
<td>2.6%</td>
<td>81%</td>
</tr>
<tr>
<td>Portugal</td>
<td>585</td>
<td>1,087</td>
<td>1,716</td>
<td>2.3%</td>
<td>83%</td>
</tr>
<tr>
<td>France</td>
<td>386</td>
<td>775</td>
<td>1,585</td>
<td>2.1%</td>
<td>85%</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>41,634</strong></td>
<td><strong>51,303</strong></td>
<td><strong>63,203</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Percent of World</strong></td>
<td>86.9%</td>
<td>86.4%</td>
<td>85.1%</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Size of commercial wind turbines at first market introduction
### Global Average Annual WTG in kW

<table>
<thead>
<tr>
<th>Year</th>
<th>China</th>
<th>Denmark</th>
<th>Germany</th>
<th>India</th>
<th>Spain</th>
<th>Sweden</th>
<th>UK</th>
<th>USA</th>
</tr>
</thead>
<tbody>
<tr>
<td>2002</td>
<td>709</td>
<td>1,443</td>
<td>1,397</td>
<td>553</td>
<td>845</td>
<td>1,112</td>
<td>843</td>
<td>893</td>
</tr>
<tr>
<td>2003</td>
<td>726</td>
<td>1,988</td>
<td>1,650</td>
<td>729</td>
<td>872</td>
<td>876</td>
<td>1,773</td>
<td>1,374</td>
</tr>
<tr>
<td>2004</td>
<td>771</td>
<td>2,225</td>
<td>1,715</td>
<td>767</td>
<td>1,123</td>
<td>1,336</td>
<td>1,695</td>
<td>1,309</td>
</tr>
<tr>
<td>2005</td>
<td>897</td>
<td>1,381</td>
<td>1,634</td>
<td>780</td>
<td>1,105</td>
<td>1,126</td>
<td>2,172</td>
<td>1,466</td>
</tr>
<tr>
<td>2006</td>
<td>931</td>
<td>1,875</td>
<td>1,848</td>
<td>926</td>
<td>1,469</td>
<td>1,138</td>
<td>1,953</td>
<td>1,667</td>
</tr>
</tbody>
</table>

### Segmentation of product sizes in 2004-2006

<table>
<thead>
<tr>
<th>Product (Size range)</th>
<th>2004</th>
<th>2005</th>
<th>2006</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total MW supplied</td>
<td>8,508</td>
<td>11,338</td>
<td>16,007</td>
</tr>
<tr>
<td>&quot;Small WTGs&quot; &lt;750 kW</td>
<td>5.4%</td>
<td>3.6%</td>
<td>2.4%</td>
</tr>
<tr>
<td>&quot;One-MW &quot; 750-1500 kW</td>
<td>50.9%</td>
<td>48.2%</td>
<td>43.3%</td>
</tr>
<tr>
<td>&quot;Mainstream&quot; 1501-2500 kW</td>
<td>42.8%</td>
<td>45.8%</td>
<td>49.9%</td>
</tr>
<tr>
<td>&quot;Multi-MW Class&quot; &gt;2500 kW</td>
<td>0.9%</td>
<td>2.4%</td>
<td>4.3%</td>
</tr>
<tr>
<td>Total</td>
<td>100.0%</td>
<td>100.0%</td>
<td>100.0%</td>
</tr>
</tbody>
</table>

Top-10 Suppliers in 2006
% of the total market 15,016 MW

- GE WIND (US) 15.5%
- ENERCON (GE) 15.4%
- GAMESA (ES) 15.6%
- SUZLON (Ind) 7.7%
- SIEMENS (DK) 7.3%
- ACCIONA (ES) 3.2%
- REPOWER (GE) 3.2%
- NORDEX (GE) 3.4%
- VESTAS (DK) 28.2%
- Others 4.6%
- GOLDWIND (PRC) 2.8%

UpWind Background

- **UpWind: FP6 Integrated project**
  - UpWind got Wind Energy back in the EU 6 Framework Energy Research program

- **Result of AOT.’s EWEA Thematic Network (EU-project):**
  1. EWEA Research Strategy
  2. UpWind
  3. EWEA Strategic Research Agenda
  4. Technology Platform

- Behind UpWind application were EAWE, EWEA and the partners (December 08 2004)

- Last minute saving of Wind Research Network in EU

- UpWind the glue/network and Lighthouse for EU R&D
The UpWind Project

*UpWind subtitle: Integrated Wind Turbine Design*

- Start date: 1 March 2006
- Duration: 60 months
- Costs: 22,340,000 EUR
- EC funding: 14,288,000 EUR
- Coordinator Risø National Laboratory, Denmark's Technical University
Participants from Start

39 participants

- 11 EU countries
- 10 research institutes
- 11 universities
- 7 turbine & component manufacturers
- 6 consultants & suppliers
- 2 wind farm developers
- 2 standardization bureaus
- 1 branch organisation
Partner’s first year

39 partners in UpWind Consortium from start

- Cener added (+1)
- Risø and DTU merged to DTU and RisøDTU (-1)
- Elsam sold to Dong Energy and Wattenfall (+1)
- INCO call added 3 new partners (+3):
  - ISM: Institute for Superhard Materials of the Nat. Academy of Science, Ukraine
  - IITB: Department of Civil Engineering of the Indian Inst. of Technology Bombay
  - CUMTB: China University of Mining and Technology Beijing

43 partners in UpWind Consortium May 2007

Other potential partners: NREL USA
Objective - 1

Develop and verify substantially improved design models and verification methods for wind turbine components, industry needs for future design and manufacture of:

1. Very Large Wind Turbines
2. More Cost Efficient Wind Turbines
3. Offshore wind farms of several hundred MW
Objective - 2

 Consortium **integrates the disciplines and sectors needed** for the entire development chain of wind turbine technology

- **8 Scientific Work Packages** – work programme
- **7 Integration Work Packages** – work programme

**Upscaling**

- Today: WT up to $P = 5$ MW and $D = 120$ m
- Future: WT upscaling: $P = 10$ MW and $P = 20$ MW
- Develop methods to overcome showstoppers/optimize
Organisation
Classic and integrated research approach
Advanced Flexibel Modern Organisation

WP Number
Work Package

1 Integrated design and standards
2 Metrology
3 Training & education
4 Innovative rotor blades
5 Transmission/conversion
6 Smart rotor blades
7 Upscaling

1A.1 1A.2 1A.3 1B.1 1B.2 1B.3 1B.4

Scientific integration
Technology integration

SIXTH FRAMEWORK PROGRAMME
Work Programme and Selected Results
From first UpWind Year
WP 1A1 *Integrated design and standards*

- Develop a reference **wt** and reference site conditions for communication, integration and benchmarking of outcomes of the horizontal work packages;
- Development and definition of an **integral design method** to be applied in the real design of wind turbines; and
- Development **(pre)standards** for the formal international standardization effort.
WP 1A2 Metrology

First year to create a list of measured parameters through communication with other work packages

First draft of list of parameters

The list has led to lively discussions between WPs

The final list is being reported

Next step reduce list and to

Develop method’s to reduce uncertainty
WP 1A3 and WP 1B1

Work Package 1A3 Education and Training
1. Survey of existing infrastructures related to education and training
2. Next step make a database for education and training

Work Package 1B1 Inovative rotorblades
1. Survey over *existing blade assambling methods*
2. Next step: select a assembling method and design a blade in two segments
Results from First Year
1B2 Transmission and conversion

→ WP 1B2.a – “Mechanical Transmission”

→ WP 1B2.b – “Generators”

→ WP 1B2.c – “Power Electronics”
Mechanical Transmission Modeling example
Comparison of different generator systems - 3MW wind turbine with the direct-drive and geared-drive -

Possibility to reduce the cost by DFIG 3G or 1G systems’ ?
Task 1B.2.c_1: Benchmark and concept reports on devices and converters.

Analysis of Matrix Converters

- "all silicon" AC/AC converter
- without DC-link
- formed by n x m bidirectional switches
- any of the outputs can be connected to any input phase.
- bidirectional topology, it can operate in four quadrants

Structure of a three-phase matrix converter
WP1B4 Up-scaling

- 5 MW ref. wtb
- 10 MW ref. wtb
- 20 MW ref. wtb
- WP1B2
- WP3
- WP4
- WP7
- WP9

UPSCALE

10 MW ref. wtb

COSTS

EVAL

ALL WP’s

- Cost breakdown
- Sensitivity analyses results

- Cost comparison
- Barriers
- R&D topics
WP2 Aero-dynamics and Aero-elastics

OBJECTIVES

1. Development of **nonlinear structural dynamic** models (modeling on the micromechanical scale is input from WP3).

2. **Advanced aerodynamic models** covering full 3D CFD rotor models, free wake models and improved BEM type models. (The wake description is a prerequisite for the wake modeling in WP8).

3. Models for **aerodynamic control features and devices**. (This represents the theoretical background for the smart rotor blades development in WP 1.B.3)

4. Models for analysis of **aeroelastic stability** and total **damping** including **hydroelastic interaction**

5. Development of models for computation of **aerodynamic noise**.
Deliverables to other work packages (60 months)

**Upscaling:**
- Aeroelastic modelling of scaled-up WT

**Smart rotor blades:**
- Modelling of camber line deformation
- Vortex generators

**Flow:**
- CFD models of terrain
- Wake models

**Innoblade:**
- CFD computations
- Flutter calculations
- Aeroacoustics

**Foundations:**
- Hydroelastic models
WP 4 Offshore support structures: fixed & floating
Support structure evaluation: Average results

Current designs (< 20 m): Monopile, (GBS)

Current design: 1st Jacket

Monopile ..... Jacket ..... Floating spar
Results from First Year
WP 5: Control

- Controller design and évaluation
  1. Algorithm development and evaluation
  2. Hardware testing and optimisation

- Field testing and evaluation

- Grid and farm integration
  1. Wind Farm optimization
  2. Electrical interaction in the network

- Interaction with other work packages
WP6. Remote sensing
EWEC Posters
Lidar and cup at 116m vs time, all data (unfiltered)
WP 8 Flow

• Data collection from Wind Farms - Wakes

• Comparison with existing flow models

• Participate in international standardization (IEC)
WP 9 Grid

• Emphasis on grid reliability and design conditions for WT coming from grid conditions

• Participate in international standardization (IEC)
Conclusions

• UpWind successfully started up – huge project
• Results from all Work Packages
• Integration activities are very effective

• Industry - and the Scientific communities do work very efficiently together
• European Wind Energy Research Community now well organized in UpWind
• EU Technology Platform starting up
Questions?
Wind Power Costs in Portugal
Under the Kyoto Protocol, Portugal, as an EU member state should limit the increase of their GHG emissions to 27% from 1990 levels by 2008 - 2012;

In 1990 the energy sector contributed with 67% of the total GHG emissions and, in this sector, the activities related with the electricity and heat industry with 35%;

Under the Directive on Renewable, Portugal must achieve a target of 39% of its electricity production from RES in terms of gross electricity consumption in 2010;
The Portuguese Government reinforced the promotion of hydroelectric resources and the support to the development of renewable energy resources, such as wind, mini-hydro, biomass, photovoltaic and waves;

Portugal is strongly dependent on external energy sources and the only national resources come from the renewable sources, specially the hydro sector;

The large hydro is the most important source for electricity production, but it is dependent on the climatic conditions and has been facing serious environmental obstacles;

With the marginal contributions of the remaining energy sources it is expected that the wind power sector will be very important for the objectives fulfilment.
Portuguese Electricity System

Public Electricity System (PES)

<table>
<thead>
<tr>
<th>Hydro Production</th>
<th>PES Central</th>
<th>NES Central</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coal</td>
<td>1776</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fuel+Diesel</td>
<td>1673</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fuel/Gas</td>
<td>236</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Natural Gas</td>
<td>2166</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>5851</strong></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Thermal Production</th>
<th>PES Central</th>
<th>NES Central</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coal</td>
<td>1776</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fuel+Diesel</td>
<td>1673</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fuel/Gas</td>
<td>236</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Natural Gas</td>
<td>2166</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>5851</strong></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Special Regime Production</th>
<th>PES Central</th>
<th>NES Central</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal</td>
<td>1159</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hydro</td>
<td>333</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wind</td>
<td>896</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>2388</strong></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Installed Power (PES/NES)</th>
<th>10433</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Installed Power</td>
<td>12821</td>
</tr>
</tbody>
</table>

**Independent Electricity System (IES)**

- Non-binding Electricity System (NES)
- Special Regime Producers (SRP) – cogeneration and renewable plants

SPR reached 18.5% of the total installed power and represent almost 14% of the total electricity production.

*Figure 1. Installed power, in Portugal (Source: REN).*
Renewable Energy Source

Table 1. National targets for the electricity production from RES.

<table>
<thead>
<tr>
<th>Renewable Source</th>
<th>2004 (MW)</th>
<th>2010 (MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wind</td>
<td>616</td>
<td>4,700</td>
</tr>
<tr>
<td>Small hydro (≤ 10 MW)</td>
<td>265</td>
<td>400</td>
</tr>
<tr>
<td>Large hydro (≥ 10 MW)</td>
<td>4,294</td>
<td>5,000</td>
</tr>
<tr>
<td>Biomass</td>
<td>456</td>
<td>330</td>
</tr>
<tr>
<td>Photovoltaic</td>
<td>2</td>
<td>150</td>
</tr>
<tr>
<td>Tide</td>
<td></td>
<td>50</td>
</tr>
<tr>
<td>Total</td>
<td>5,633</td>
<td>10,630</td>
</tr>
</tbody>
</table>

In 2010, hydro will maintain a dominant position, but its share will be reduced largely due to the increase of the wind sector.
Wind Power Sector

The average annual rate (1999 – 2005) was 67%.

This source of energy represented:
- 20% of the renewable electricity production
- 3,3% of the total electricity production

Portugal is still distant of the European leaders, namely from:
- Germany – 18 GW
- Spain – 10 GW
- Denmark – 3 GW

Figure 2. Installed and cumulative wind power, in Portugal (Source: DGGE, 2006).
Portuguese Electric Power System

**Wind Power Sector**

To reach the national objectives it is necessary:
- to install an average of 732 MW/year
- to grow to an annual average rate ≈ 36%

Although the great potential, some barriers exist:
- delays in the licensing processes;
- difficulties on the access to the grid.
Cost Analysis

Method

The equation used to calculate the *Levelized Electricity Generation Cost* (EGC) is:

\[
EGC = \frac{\sum (I_t + M_t + F_t + X_t) (1+r)^{-t}}{\sum E_t (1+r)^{-t}}
\]

were:

EGC – Average lifetime levelized electricity generation cost
I<sub>t</sub> – Investment expenditure in the year <i>t</i>
M<sub>t</sub> – Operations and maintenance expenditure in the year <i>t</i>
F<sub>t</sub> – Fuel expenditure in the year <i>t</i>
X<sub>t</sub> – External expenditure in the year <i>t</i>
E<sub>t</sub> – Electricity generation in the year <i>t</i>
r – Discount rate
Data Sources

Table 2. Data and system characteristics of wind farm and CCGT.

<table>
<thead>
<tr>
<th></th>
<th>Wind</th>
<th>CCGT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Installed capacity</td>
<td>20 MW</td>
<td>1200 MW</td>
</tr>
<tr>
<td>Load factor</td>
<td>22%</td>
<td>85%</td>
</tr>
<tr>
<td>Thermal efficiency</td>
<td>-</td>
<td>57%</td>
</tr>
<tr>
<td>Life time</td>
<td>20 years</td>
<td>25 years</td>
</tr>
<tr>
<td>Investment costs</td>
<td>1206.20 €/kW</td>
<td>514.19 €/kW</td>
</tr>
<tr>
<td>O&amp;M annual costs</td>
<td>15.37 €/kW</td>
<td>23.59 €/kW</td>
</tr>
<tr>
<td>Fuel costs</td>
<td>-</td>
<td>22.23 €/MWh</td>
</tr>
</tbody>
</table>

Table 3. External costs for different damage estimates (ExternE).

<table>
<thead>
<tr>
<th>External costs</th>
<th>Wind (€/MWh)</th>
<th>CCGT (€/MWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>0.02 – 0.07</td>
<td>1.93</td>
</tr>
<tr>
<td>Mid 3%</td>
<td>0.11 – 0.31</td>
<td>9.41</td>
</tr>
<tr>
<td>Mid 1%</td>
<td>0.29 – 0.81</td>
<td>24.02</td>
</tr>
<tr>
<td>High</td>
<td>0.87 – 2.44</td>
<td>72.54</td>
</tr>
</tbody>
</table>

- constant pricing was used.
- based on the 2005 value.
- discount rate of 5 and 10%.

Not included:
- backup capacity to compensate wind intermittency and fluctuations;
- reinforce the distribution and transmission systems;
- feed-in tariffs.
### Results

#### Discussion of the Results

#### Conclusions

#### Costs Analysis

### Table 4. Annual levelized costs for the two technologies.

<table>
<thead>
<tr>
<th>Costs</th>
<th>Wind</th>
<th>CCGT</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(€/kW)</td>
<td>(€/MWh)</td>
</tr>
<tr>
<td>1. Investment</td>
<td></td>
<td></td>
</tr>
<tr>
<td>r = 5%</td>
<td>1206.20</td>
<td>50.23</td>
</tr>
<tr>
<td>r = 10%</td>
<td></td>
<td>73.52</td>
</tr>
<tr>
<td>2. O&amp;M</td>
<td></td>
<td></td>
</tr>
<tr>
<td>r = 5%</td>
<td>15.37</td>
<td>7.98</td>
</tr>
<tr>
<td>r = 10%</td>
<td></td>
<td>7.98</td>
</tr>
<tr>
<td>3. Fuel</td>
<td></td>
<td></td>
</tr>
<tr>
<td>r = 5%</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>r = 10%</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>4. External</td>
<td></td>
<td></td>
</tr>
<tr>
<td>low</td>
<td>0.02 – 0.07</td>
<td></td>
</tr>
<tr>
<td>mid 3%</td>
<td>0.11 – 0.31</td>
<td></td>
</tr>
<tr>
<td>mid 1%</td>
<td>0.29 – 0.81</td>
<td></td>
</tr>
<tr>
<td>high</td>
<td>0.87 – 2.44</td>
<td></td>
</tr>
<tr>
<td>Total cost (no external)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>r = 5%</td>
<td>58.21</td>
<td>47.05</td>
</tr>
<tr>
<td>r = 10%</td>
<td>81.50</td>
<td>49.76</td>
</tr>
<tr>
<td>Total cost (with external)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>r = 5%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>low</td>
<td>58.23 – 58.28</td>
<td></td>
</tr>
<tr>
<td>mid 3%</td>
<td>58.32 – 58.52</td>
<td></td>
</tr>
<tr>
<td>mid 1%</td>
<td>58.50 – 59.02</td>
<td></td>
</tr>
<tr>
<td>high</td>
<td>59.08 – 60.65</td>
<td></td>
</tr>
<tr>
<td>r = 10%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>low</td>
<td>81.52 – 81.57</td>
<td></td>
</tr>
<tr>
<td>mid 3%</td>
<td>81.61 – 81.81</td>
<td></td>
</tr>
<tr>
<td>mid 1%</td>
<td>81.79 – 82.31</td>
<td></td>
</tr>
<tr>
<td>high</td>
<td>82.37 – 83.94</td>
<td></td>
</tr>
</tbody>
</table>
Not including external costs it can be verified that:

- Investment and O&M costs of wind power plants are considerably higher than the gas technology;
- Load factor of renewable energy is low when compared with the CCGT system;

\[ \text{CCGT is more attractive than the wind technology} \]

**Figure 3.** Estimated cost structure for wind plant (5% and 10% discount rate).

**Figure 4.** Estimated cost structure for CCGT (5% and 10% discount rate).
Analysis and Discussion of the Results

Including external costs it can be verified that:

- In wind technology the investment costs still represent a high proportion (% total cost);
- In gas technology the fuel costs have a significant weight for low estimates, but in high estimates the external costs are the one that most contribute to the total cost;

CCGT continues to be more attractive than the wind technology, except for high estimates.

**Figure 5.** Estimated cost structure for wind plant (5% and 10% discount rate).

**Figure 6.** Estimated cost structure for CCGT (5% and 10% discount rate).
Sensitive Analysis

- **Discount rate:**
  The CCGT technology is less affected by the variation of the discount rate.

- **O&M escalation rate:**
  The increase of the total costs diminishes as the load factor increases (the percentage of the costs of O&M is smaller).

- **Fuel escalation rate:**
  The total costs for the CCGT increase significantly, being more accentuated for lower discount rates and for larger load factors.

- **Load factor:**
  The larger the load factor the lower the production costs. The reduction of the costs is less accentuated in the CCGT system than in the wind system.
Conclusions

- CCGT is still more attractive than the wind energy when only financial aspects are accounted for.

- When external costs are considered, the electricity generation costs for the two technologies are similar.

- However, for high estimates (of GHG emissions) the wind system reaches more attractive values.

- The sensitivity analysis showed that:
  - the increasing of fuel escalation rates is the parameter that originates larger effects in the Levelized Electricity Generation Cost.
  - the Levelized Electricity Generation Cost (without environmental costs) of a wind farm is more positively influenced by the load factor than the CCGT system.
The results were obtained assuming 2005 constant values. However, in the near future, it can be expected:
- an increase on conventional systems costs
- a decrease on renewable systems costs
- an increase of the natural gas price (almost 84% between 2003 and 2005)

The expansion of the wind technology in Portugal will influence significantly the energy system costs, but it is fundamental for the attainment of the European and National Energy and Environment goals.

The expectations and incentives around the wind energy are comprehensible:
- it is a renewable energy source
- the reduction of the investment costs expectedly may turn this technology economically attractive to the investors
- if the life cycle is analysed, and the external costs included, it can become more advantageous than the conventional systems.
- the increase of the fossil fuel prices is creating a new competitive advantage for wind power systems.
THANKS
Economic and Financial Feasibility of Wind Energy - Case Study of Philippines

Risø International Energy Conference 2007, 22 - 24 May

(Presentation is based on the work carried out under the EU-Asean Facility funded project: Feasibility Assessment and Capacity Building for Wind Energy Development in Cambodia, the Philippines and Vietnam)

Jyoti Prasad Painuly
Energy Policy in Philippines

- 60% self-sufficiency by 2010 (55.5% 2004)

- Increase 100% RE based capacity in 10 years (to reach 9147 MW in 2003)

- Wind Energy;
  - 425 MW in 10 years (2005 base year)
  - 16 sites in Wind Investment Kit

- Renewable Energy Bill 2006
  - Renewable portfolio standard
  - Green energy option for end users
  - Net metering
Clean energy funds
Fiscal incentives- IT holidays, duty rebates, VAT rebate etc.

- Wind Energy Potential
  - Initial assessment 76000 MW (NREL)
  - Realizable 7400 (WWF)
  - Target for 10 years; 425MW
    - First wind energy investment kit; 345 MW
    - Installed 25MW (Northwind in Luzon)
Sites in the Philippines

St. Ana

Dinagat Island

Source: Niels-Erik Clausen, Wind Energy, RISØ presentation
Sta. Ana

The mast is located 10 m asl
Measurement heights 10 and 27 m

Source: Niels-Erik Clausen, Wind Energy, RISØ presentation
Location and wind data

- St. Ana (30 MW)
  - Cagayan region (Luzon Island)
  - Zone 1 (wind upto 70 m/sec)

- Wind Data
  - Mean wind speed 4.9 m /sec (8 months; Sept 2005-April measurements)
  - Max. 18m /sec

- Est. Generation
  - 80 GWh /yr (57-79, depending on location) using 2 MW V66/67 m wind turbine
  - 60MWh/ yr (43-61) using 2MW V80/67
# Financial Analysis of St. Ana Wind Power Project

| Background |  
|------------|--------------------------------------------------|
| Investment | $51.8 mill. Includes feasibility study, project and site development work, engineering, plant and equipments, installation, transmission lines (1$=52 P) |
| O & M Costs | $1.1 mill. per year. includes land lease, property tax, labour, other operational expenses etc. |
| (increase 3% per year) | |
| Annual Energy Production | **80 GWh** (net) |
| - 7% losses (Transmission) | |
| -- From year 1, above AEP | |
| Plant life | 20 years- 10% Salvage Value |
| Income tax | - No tax for 6 years  
|           | - 30% after that |
| Projected power sale rate | P 4.91 / kWh  
|           | (and escalation 3% per year) |
| CDM       | $6/ ton and $10/ton  
|           | 0.625 t/ MWh |
| Note: CDM revenues assumed for entire plant life |
Financial Structuring

Ownership Structures

- Private
- Utility
- Public (Central or Provincial)

Each has its own costs and financial arrangement possibilities.

Base Case:
Equity 20%
Loan 80%; 8%, 15 Yrs + 6 Yr (Grace Period)
NPV and IRR Calculations

- Discount rate
  - Hurdle rate was calculated based on cost of financing
  - 8.68% (base case)
Hurdle rate

- Required IRR >= hurdle rate
- The hurdle rate is weighted average cost of the capital (WACC) + spread
- WACC is calculated using the following formula:
  \[ WC = \left( \frac{E}{TC} \right) \times RE + \left( \frac{D}{TC} \right) \times RD \times (1-T) \]
  Where:
  - WC is weighted average cost of capital
  - E is the equity contribution
  - D is the debt
  - TC is the total cost (D+E)
  - RE is the required return on equity (11%)
  - RD is required rate of return on debt (rate of interest + FE risk (1.5%) and guarantee (2%) for foreign loans), and
  - T is the tax rate (30%)

Discount rate = Hurdle rate + spread (2%)

11
### 80GWh site location

<table>
<thead>
<tr>
<th><strong>NPV</strong></th>
<th><strong>IRR</strong></th>
</tr>
</thead>
</table>
| **Base Case:** Discount rate 8.68%  
  (Domestic loan at 8% with 15 year term + 6 yr GP) | **9.83%**    |
| Discount rate **13.2%**          | **(Northwind 9.3%, tariff P 4.43/kWh; 1 USD = 57P)** |
| (Risk adjusted)                  |               |
| Which one to choose?             |               |
| **P 243 Mill.**                  | **7.56**      |
| **(P 553 mill)**                 |               |
Check

- Impact of CDM

<table>
<thead>
<tr>
<th>CER Prices</th>
<th>$6/ton</th>
<th>$10/ton</th>
</tr>
</thead>
<tbody>
<tr>
<td>IRR</td>
<td>10.46</td>
<td>10.87</td>
</tr>
<tr>
<td>MIRR</td>
<td>7.78</td>
<td>7.93</td>
</tr>
</tbody>
</table>

Is it acceptable now?
What is my acceptable IRR? 17-18% private investors?

This is economic IRR, and if tariff and investment and other data is without distortion, it gives a basis for decision making at policy level (although it is not strictly an economic analysis).

For an investor, decision criteria will typically be Financial IRR, which depends on financing arrangements.

Analysis - nominal v/s real
### Table 1: Base Case and Variations (NPV in million P)

<table>
<thead>
<tr>
<th>Indicator</th>
<th>Base case</th>
<th>Elect Tariff +10%</th>
<th>Investment +20%</th>
<th>El. Gen. - 20%</th>
<th>O&amp;M costs +20%</th>
</tr>
</thead>
<tbody>
<tr>
<td>NPV 8.68% (hurdle rate)</td>
<td>243</td>
<td>614</td>
<td>-230</td>
<td>-385</td>
<td>138</td>
</tr>
<tr>
<td>With CDM; $6/t</td>
<td>379</td>
<td>750</td>
<td>-95</td>
<td>-276</td>
<td>273</td>
</tr>
<tr>
<td>With CDM $10/t</td>
<td>469</td>
<td>840</td>
<td>-5</td>
<td>-204</td>
<td>364</td>
</tr>
<tr>
<td>NPV 13.2%</td>
<td>-553</td>
<td>-278</td>
<td>-1052</td>
<td>-1020</td>
<td>-632</td>
</tr>
<tr>
<td>With CDM; $6/t</td>
<td>-453</td>
<td>-178</td>
<td>-951</td>
<td>-939</td>
<td>-531</td>
</tr>
<tr>
<td>With CDM $10/t</td>
<td>-386</td>
<td>-110</td>
<td>-884</td>
<td>-885</td>
<td>-464</td>
</tr>
<tr>
<td>IRR</td>
<td>9.83%</td>
<td>11.53%</td>
<td>7.75%</td>
<td>6.79%</td>
<td>9.33%</td>
</tr>
<tr>
<td>With CDM; $6/t</td>
<td>10.46%</td>
<td>12.14%</td>
<td>8.30%</td>
<td>7.33%</td>
<td>9.97%</td>
</tr>
<tr>
<td>With CDM; $10/t</td>
<td>10.87%</td>
<td>12.54%</td>
<td>8.66%</td>
<td>7.69%</td>
<td>10.39%</td>
</tr>
<tr>
<td>MIRR</td>
<td>7.56%</td>
<td>8.16%</td>
<td>6.75%</td>
<td>6.35%</td>
<td>7.37%</td>
</tr>
<tr>
<td>With CDM; $6/t</td>
<td>7.78%</td>
<td>8.36%</td>
<td>6.97%</td>
<td>6.58%</td>
<td>7.61%</td>
</tr>
<tr>
<td>With CDM; $10/t</td>
<td>7.93%</td>
<td>8.50%</td>
<td>7.11%</td>
<td>6.72%</td>
<td>7.76%</td>
</tr>
<tr>
<td>IRR-Investor</td>
<td>14.03%</td>
<td>21.08%</td>
<td>7.28%</td>
<td>4.71%</td>
<td>12.26%</td>
</tr>
<tr>
<td>With CDM; $6/t</td>
<td>16.47%</td>
<td>23.93%</td>
<td>8.89%</td>
<td>6.13%</td>
<td>14.57%</td>
</tr>
<tr>
<td>With CDM; $10/t</td>
<td>18.19%</td>
<td>25.89%</td>
<td>10.02%</td>
<td>7.11%</td>
<td>16.20%</td>
</tr>
</tbody>
</table>
# Financing Scenarios

<table>
<thead>
<tr>
<th>S.No.</th>
<th>Financing scheme</th>
<th>Discount rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>B</td>
<td>Base case; Domestic loan at an interest rate of 8%, 15 year term with a grace period of 6 years</td>
<td>8.68</td>
</tr>
<tr>
<td>F1</td>
<td>Loan, financed through ODA at 0.3% for 20 years, with a grace period of 10 years.</td>
<td>6.33</td>
</tr>
<tr>
<td>F2</td>
<td>JBIC ODA at 0.90% for 20 years and a grace period of 6 years (untied, as applicable to Philippines; <a href="http://www.jbic.go.jp/english/oec/standard/">http://www.jbic.go.jp/english/oec/standard/</a>)</td>
<td>6.66</td>
</tr>
<tr>
<td>F3</td>
<td>OECD commercial loan at 5% for 10 years, with a grace period of 1 year (construction period).</td>
<td>8.96</td>
</tr>
<tr>
<td>F4</td>
<td>Danida financing; 35% grant and balance 65% as loan at 7%, 10 year term</td>
<td>9.80</td>
</tr>
</tbody>
</table>
### Table 3: Financing Scenarios

<table>
<thead>
<tr>
<th>Indicator</th>
<th>Base case</th>
<th>F1</th>
<th>F2</th>
<th>F3</th>
<th>F4</th>
</tr>
</thead>
<tbody>
<tr>
<td>DBP</td>
<td>8%; 15 yr, GP 6 yr</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ODA</td>
<td>0.3%; 20 yr, GP 10 yrs</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>F1</td>
<td>0.9%; 20 yr, GP 6 yrs</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>OECD 5%; 10 yr, GP 1 yr</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Danida 7%; 10 yr</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(grant 35%), No GP</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NPV 13.2%</td>
<td>-553</td>
<td>-616</td>
<td>-610</td>
<td>-609</td>
<td>66</td>
</tr>
<tr>
<td>With CDM; $6/t</td>
<td>-453</td>
<td>-516</td>
<td>-510</td>
<td>-508</td>
<td>167</td>
</tr>
<tr>
<td>With CDM; $10/t</td>
<td>-386</td>
<td>-448</td>
<td>-443</td>
<td>-441</td>
<td>234</td>
</tr>
<tr>
<td>Hurdle rate</td>
<td>8.68%</td>
<td>6.33%</td>
<td>6.66%</td>
<td>8.96%</td>
<td>9.80%</td>
</tr>
<tr>
<td>NPV</td>
<td>243</td>
<td>753</td>
<td>667</td>
<td>103</td>
<td>567</td>
</tr>
<tr>
<td>With CDM; $6/t</td>
<td>379</td>
<td>915</td>
<td>824</td>
<td>236</td>
<td>692</td>
</tr>
<tr>
<td>With CDM; $10/t</td>
<td>469</td>
<td>1023</td>
<td>930</td>
<td>324</td>
<td>776</td>
</tr>
<tr>
<td>IRR</td>
<td>9.83%</td>
<td>9.41%</td>
<td>9.45%</td>
<td>9.46%</td>
<td>13.76%</td>
</tr>
<tr>
<td>With CDM; $6/t</td>
<td>10.46%</td>
<td>10.05%</td>
<td>10.09%</td>
<td>10.10%</td>
<td>14.60%</td>
</tr>
<tr>
<td>With CDM; $10/t</td>
<td>10.87%</td>
<td>10.47%</td>
<td>10.51%</td>
<td>10.52%</td>
<td>15.15%</td>
</tr>
<tr>
<td>MIRR</td>
<td>7.56%</td>
<td>7.40%</td>
<td>7.41%</td>
<td>7.41%</td>
<td>8.81%</td>
</tr>
<tr>
<td>With CDM; $6/t</td>
<td>7.78%</td>
<td>7.63%</td>
<td>7.65%</td>
<td>7.65%</td>
<td>9.06%</td>
</tr>
<tr>
<td>With CDM; $10/t</td>
<td>7.93%</td>
<td>7.78%</td>
<td>7.80%</td>
<td>7.80%</td>
<td>9.22%</td>
</tr>
<tr>
<td>IRR-Investor</td>
<td>14.03%</td>
<td>50.73%</td>
<td>45.17%</td>
<td>13.32%</td>
<td>21.33%</td>
</tr>
<tr>
<td>With CDM; $6/t</td>
<td>16.47%</td>
<td>53.50%</td>
<td>48.20%</td>
<td>14.71%</td>
<td>23.24%</td>
</tr>
<tr>
<td>With CDM; $10/t</td>
<td>18.19%</td>
<td>55.34%</td>
<td>50.19%</td>
<td>15.67%</td>
<td>24.54%</td>
</tr>
</tbody>
</table>
Lessons Learnt

Lessons learnt in the case study:

- St. Ana is not viable as a normal project; load factor at 30% is reasonable.

- Uncertainties (investment cost, O&M cost, and generation) make it a risky venture even with favourable financing packages.

- A combination of soft financing and high CDM revenues can make it viable.
Conclusions

- Economic viability of wind energy is an issue in Philippines
- Nationally, development of wind can be justified from energy security perspective
- Development of wind energy for global environmental reasons may require carbon financing, supplemented through grants / soft financing, wherever necessary.
More info; www.aseanwind.eu

THANK YOU

Contact;
J.P. Painuly
UNEP Risoe Centre
j.p.painuly@risoe.dk
Wave Energy
– challenges and possibilities

By: Per Resen Steenstrup
www.WaveStarEnergy.com
Wave energy is an old story….

The first wave energy patent is 200 years old. Over the last 100 years more than 200 new wave energy devices have been developed and more than 1,000 patents have been issued. Over the last 30 years more than 400 million EUR have been spent on demonstrators in the sea, with little or no success. Only in the last 5 years the practical solutions have started to show, with real chances of commercialisation.

**Main features for success:**
- Simple storm protection concept.
- Proven technology in the sea.
- Simple and reliable concept, with simple power take off system.
- Scalable to big MW systems in the future.
- Low weight per MW - potential for future cost reductions.
Wave energy concepts World wide, which have been tested in the sea

Oscillating water column – floating or fixed coastal installation. Air based Wells turbines as power take off.

Overtopping waves into a reservoir, with low head turbines as power take off.

Articulating tubes with hydraulic power take off.

Point absorber, with either water pumps, linear generators or hydraulic power take off systems.

Multi point absorbers, with hydraulic power take off.
AIR TURBINE

COMPRESSED AIR

OSCILLATING WATER COLUMN

WAVE DIRECTION

SEA BED
OVER TABBING RESERVOIR

LOW HEAD TURBINE

MOORING

SEA BED
ARTICULATING TUBES WITH HYDRAULIC JOINTS

MOORING

WAVE DIRECTION

SEA BED
Wave Star’s background in head lines.

Wave Star Energy was established October 1st 2003, with the sole purpose of commercialising wave energy.

Over a period of 10 months in 2004 a scale 1:40 converter was extensively tested in regular as well as irregular waves, to document the configuration, optimize the power output and document dynamic behavior compared to a hydro dynamic model.

Based on the extensive tank testing a scale 1:10 converter was designed and built during 2005 and deployed in the sea on April 6th 2006 at Nissum Bredning (DK). The converter was built and instrumented to the same high standard as a full scale converter.

After initial testing of all sub systems the converter was grid connected and put into unattended operation on July 24st 2006.

It has been in operation since then and logged more than 6,000 hours.
What is special about the Wave Star concept?

It is a simple reliable design, which can be storm protected. It sits on piles, just like an offshore structure.

All moving parts are above water and are well protected from the sea environment.

It is only based on standard components and standard offshore - and wind turbine technology.

It is scalable into multi MW converters.

Price and electric production per MW makes it realistic to become commercial over time, and supplement wind turbines on a big scale.
Wave Star in normal operation
Wave Star in storm protection mode
How does the power scale with size?

The test converter in Nissum Bredning is a scala 1:10 converter. It is 24 m long with 40 floats of each Ø 1m, and operates in 2 m of water. In **0,5 m Hs** the power output is **1.800 W** electric power.

The scale 1:2 converter is 120 m long with 40 floats of Ø 5 m and operates in 10 m of water depth. In **2,5 m Hs** the power output is **500 kW**.

The scale 1:1 converter is 240 m long with 40 floats of each Ø10 m and operates in 20 m of water. In **5,0 m Hs** the power output is **6 MW**.

The scale 1,5 :1 converter is 360 m long with 40 floats of each Ø 15 m and operates in 30 m of water. In **7,5 m Hs** the power output is **24 MW**.
What are the plans for the future?

The scale 1:10 converter in Nissum Bredning will continue to operate until August 2008. The goal is to optimize the energy production and obtain long term working experience.


Arms and floats for the 500 kW converter will be installed and tested at a pier in the North Sea in 2008.

The scale 1:2, 500 kW will be pre installed at the North of Lolland at Onsevig i 2008 / 2009.

Later transferred and installed at Horns Rev (North Sea) in 2009.
Section of 500 kW machine will be installed here
Horns Rev installation

500 kW Wave Star machine
What are the major challenges for Wave Star in reaching a commercial break through?

Install and operate the first commercial 500 kW Wave Star Energy machine at Horns Rev i 2009 /2010, without any major technical problems or short commings.

Through cost engineering, in the early development phase of the 500 kW machine, bring the kWh cost down to less than 20 EUR cent, even when the machine is operated in 10 m of water depth and in a low wave climate of only 4 kW / m, in average.

Improve realiability of the first 500 kW machine, to make it the most reliable machine in the market.

Scale the machines in small steps to minimize risk. 500 kW, 1,5 MW, 3,0 MW, 6MW, 10 MW, 15 MW, 20MW etc.
Visit by the Danish Deputy Prime Minister on the 13th of April 2007
Operational costs induced by fluctuating wind power production in Germany and Scandinavia

Peter Meibom, Risø, Technical University of Denmark
Christoph Weber, University Duisburg-Essen
Rüdiger Barth & Heike Brand, IER, University of Stuttgart
Overview presentation

- Purpose of the study
- Methodology
- Results
- Discussion of integration costs
- Outlook
Purpose of study

• Analyse the impact on operational costs from increased wind power in Germany and the Nordic countries
• Part of the so-called integration costs of wind power:
  • Grid reinforcements
  • Investment in balancing power plants
  • Increase in operational costs due to more variable operation of conventional plants
Definition of integration costs of wind power

• Difference between
  • Expected reduction in system costs (need clarification)
  • Realised reduction in system costs
• Expected reduction? (often reduction achieved with dispatchable technology):
  • Gas turbine with same energy production as wind production
  • Constant production with same energy production as wind production
Methodology

• Calculations with the Wilmar Planning tool (www.wilmar.risoe.dk)
• Compare operational costs in three model runs:
  1. With stochastic wind power production
  2. With deterministic wind power production
  3. With constant wind power production
• 1 minus 2: Costs of partial predictability
• 2 minus 3: Costs of variability
• 1 minus 3: Integration costs of wind power
• Each model run covers 5 selected weeks
Overview Planning tool
Overview of the Planning Tool
Design of Joint Market model

Rolling Planning Period 1:
Day-ahead market cleared

Rolling Planning Period 2
Methodology

- 2010 power system configuration case:
  - Yearly load
  - Transmission lines
  - Power plants
  - Fuel prices
  - CO2 price
  - Three cases for installed wind power
Installed wind power capacity in each wind scenario

[Bar chart showing wind power capacity in various regions and scenarios.]
Difference in system operation costs

![Chart showing differences in operation costs with different levels of predictability and variability. The x-axis represents different percentages (Base, 10%, 20%) and the y-axis represents cost in Euro/MWh Wind. The chart compares costs of partial predictability and variability.](chart_image)
Difference in system operation costs per MWh wind power production for the three wind cases and divided on countries.
Discussion

• Integration costs a ill-defined concept:
  • Involves comparison with a hypothetical power system configuration (e.g. constant wind power production)
  • What can the information be used for?
• We should use comparison of system costs and benefits in stead:
  • Power system configurations with different amounts of wind
  • Comparison should include:
    • Investment costs (grid and plants)
    • Operational costs
    • Emissions (CO2, …)
    • Different scenarios for fuel prices and CO2
    • Security of supply
Outlook

• The development and usage of the Wilmar Planning tool is continued in
  • SUPWIND: EU sixth framework programme project, www.supwind.risoe.dk
  • All-Island Grid study: Irish wind integration study
  • Anemos-plus: EU sixth framework programme project
• Model developments:
  • Load uncertainty
  • Forced outages
  • Unit commitment with mixed integers
  • Interaction with investment model
• Case studies:
  • Irish case
  • New Nordic and German cases
  • Probably other European cases
In Iranian historical architecture wind tower is used for cooling and ventilation. Wind tower is a tall structure that stands on building. Wind tower is used in dry land, and only uses wind energy for conditioning.
Introduction

It technologies date back over 1000 years. Wind towers were designed according to several parameters, some of the most important of which were building type, cooling space volume, wind direction and velocity and ambient temperature.
Wind tower of Doulat-Abad garden of Yazd with its altitude is 33 meters and 80 centimeter. It is highest wind tower in Iran. It has built in 1750. This wind tower has octagon plan. It can receive wind from eight directions and conduct it inside of room.
1) Square and octagon wind tower is suitable for regions that direction of pleasant wind is various, specially in the warm seasons that some times pleasant wind blows from north to south and some times from east to west.

*An octagon wind tower in Yazd*
2) Rectangular wind tower has built in the area that direction of wind is from north-east to south-west. For this reason architectures make it in front of big surface of outward appearance.

A rectangular wind tower in Semnan
3) In the villages of edge of desert and villages of inside of desert to avoid harm of whirlwind and storm architectures make it only direction, it has made north-east and other sides have been closed. Its direction is to the mountain breeze.
Function of wind tower basically constructed method of utilization from blowing of wind to take pleasant air in to building and use from its reflection energy to suck for drive away hot and polluted weather.
Function of Wind Tower

Dry weather that wind tower receives path above of little pool and fountain it becomes cool by method of evaporation and goes into the room.
This section indicates conclusion of inside and outside temperature of building that has equipped wind tower in one of summer hot day. This specimen ventilation has been made about 135 years ago in south of Semnan it's high is 20 meters. It is highest wind tower of Semnan.
Case Study

Room temperature comparison
Conclusion

As shown in above graph wind tower can moderate weather of room. Other important point is fixing temperature of room and keeps it in suitable situation. Above graph shown average degree of environment in the outside is $32^\circ C$ and average temperature of room is $23^\circ C$. It is desirable weather in the warm area.
Thank you very much for your attention
Energy Demand Patterns

The Effects Substitution and Productivity

Nico Bauer
Potsdam Institute for Climate Impact Research (PIK)
Contents

• Production theory
  – Substitution
  – Biased technological change
  – Separability
• Econometric framework
• Results
• Discussion and further research
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• Discussion and further research
Production Theory

• Aggregate production function \( f() \)
  - Output \( y \)
  - Inputs \( x \)
  - Prices \( p \)

\[
y = \left[ (a_1 x_1)^\rho + (a_2 x_2)^\rho \right]^{1/\rho}; \quad \sigma = (1 + \rho)^{-1} = -\frac{\partial x}{\partial p} \cdot \frac{x}{p}.
\]

• Optimal Factor Allocation
  - Marginal productivities equal prices

\[
p_i = \frac{\partial y}{\partial x_i} \quad \Leftrightarrow \quad x = \tilde{f}(p).
\]
Production Theory
Production Theory

Production function:

\[ X = f(P) \]

\[ X^0 \]

\[ P^0 \]
Production Theory

X

X^0

X^1

P

P^0

P^1

Production Theory
Production Theory

Substitution

X

X^0

X^1

P^0

P^1

P
Production Theory

Substitution

Biased TC

\[ X^0 \]

\[ X^1 \]

\[ P^0 \]

\[ P^1 \]

\[ P \]
Production Theory

\[ X \]

Substitution

Biased TC

\[ P^0 \]

\[ P^1 \]
Production Theory

\[ X \]

\[ X^0 \]

\[ X^1 \]

\[ P^0 \]

\[ P^1 \]

Substitution

Biased TC

Nico Bauer
Potsdam Institute for Climate Impact Research

Risø International Energy Conference
May 22 – 24, 2007
Production Theory

\[ \frac{\partial \left( \frac{x_1}{x_2} \right)}{\partial p_3} = 0 \]
\[ x_t = \gamma_0 + \gamma_p p_t + \gamma_t + \varepsilon_t. \]

\[ \Delta x_t = \beta_0 + \beta_p p_t + \varepsilon_t, \text{ where } \Delta x_t = x_t - x_{t-1}. \]

\[ x_t = \beta_0 + \beta_p \Delta p_t + \beta_t t + \varepsilon_t, \text{ where } \Delta p_t = p_t - p_{t-1}. \]

\[ \Delta x_t = \beta_0 + \beta_p \Delta p_t + \varepsilon. \]

\[ \Delta x_t = \beta_0 + \beta_p \Delta p_t + \beta_e (x_{t-1} - \gamma_0 - \gamma_p p_{t-1} - \gamma_t) + \nu_t. \]
Results – Overview

• Nearly all energy ratios are trended; not so much price ratios

• High share of ratios is non-stationary ➔ models with differences

• Substitution: rarely significant

• BTC: significant with many structural breaks
Results – Gas-Oil

• Trend to gas ➔ Ö, Bel, CH, J, NL, SP
• Slowed down ➔ Cz93, F85, D85, I92, UK89
• Switch to oil ➔ Sl92, USA88
• Trend to oil ➔ Mex

• 3 of 24 substitution parameters significant, …
• One having the wrong sign.
Results – Gas-Coal

- Trend to coal ➔ Bel
- Trend to gas ➔ F, J, SI, US
- Accelerated ➔ CH91, D89, UK92
- Slowed down ➔ Cz92
- Switch to gas ➔ Ö85, I85
- Switch to coal ➔ T93

- 2 of 21 substitution parameters significant
Results – Oil-Coal

- Trend to coal ➔ Ö, Bel, NL, Nor
- Trend to oil ➔ Cz, J, UK, SI
- Switch to oil ➔ CH87, F90, D89, I85, US91

- 6 of 22 substitution parameters significant, …
- One having the wrong sign.
Discussion

• Low evidence for substitution

• High evidence for BTC; structural breaks

• Countries show different patterns

• What may explain BTC?
Discussion

- Investments and depreciation re-structure capital stock
- Changes relative energy demands
- Investments determined not only by energy prices
- Contradiction with separability assumption!
- BTC can capture changed energy demand due to capital stock restructuring
- Problem: how to endogenise BTC?
Further Research

• Improvement of data
  – Sectoral resolution
  – Investment data

• Theoretical analysis
  – Bottom-up vs. top-down ➔ capital theory
  – Separability and BTC

• Integrated modeling
  – Pragmatic approach: exogenous BTC
  – Scenarios, sensitivity analysis
STREAM: 
A Model for a Common Energy Future


Peter Markussen
DONG Energy Generation
Background

• The future Danish Energy System (2004-2007)
• Initiated by The Danish Board of Technology
  – Public body established by the Danish parliament

• Project content
  – Open scenario process
  – Quantification of scenarios
  – www.tekno.dk
Goal of the project

• Lay dawn objective and possible futures for the Danish Energy System

• Steering group to agree on the process and overall goals for scenarios
  – 10 interested parties from the energy sector and NGO’s

• Working group to supply a modeling tool and facts:
  – Mette Behrmann, Jens Pedersen (Energinet.dk)
  – Kenneth Karlsson (Risø)
  – Anders Kofoed-Wiuff, Jesper Werling (EA Energianalyse)
  – Peter Markussen (DONG Energy)
Agenda

1. The scenario process
2. The results
3. The modelling tool
   • Energy savings model
   • The time series model
   • The energy flow model
4. Perspectives
Agenda

1. The scenario process
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4. Perspectives
The scenario process

1 Public hearing
Global, regional and national challenges for the energy sector

2 Public hearing
Danish energy production in the future

3 Public hearing
Danish energy demand in the future

4 Public hearing
Presentation of 4 technological developments paths and a combination scenario

Workshop with politicians on measures to promote:
- Wind
- Electrification of road transport
- Energy savings on public buildings
- Use of bio gas
- Future of public heating infrastructure

Final conference

Project start

2004

2005

2006

2007
Quantitative targets

• Reduce CO2 emissions by 50% in 2025 compared to 1990
• Reduce oil consumptions by 50% in 2025 compared to 2003
• Take into account global responsibility and national economics
Agenda

1. The scenario process
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4. Perspectives
4 technological scenarios to 2025

**Cost savings**
- Energy savings
- Zero energy buildings

**Gas**
- Gas for electricity and CHP
- Micro CHP
- Gas for transport

**Wind**
- Off shore wind
- Flexible electricity demand
- Electricity/hydrogen for transport

**Biomass**
- Biomass for electricity and heat
- Biomass for transport
- Biomass for heating

**Reference**
“Business As Usual”
Development based on fuel prices

*Cost savings* and *Wind* are marked as *A+*.
The Combination scenario

- Combination of the 4 technology scenarios
- Inspiration from the workshop with politicians
- Savings and increased electricity production from wind and biomass for transport. Gas as back up for wind.
The Combination Scenario
Fuel use

<table>
<thead>
<tr>
<th>Year</th>
<th>Oil</th>
<th>Coal and carbonized coal</th>
<th>Renewable energy etc.</th>
<th>Natural gas</th>
</tr>
</thead>
<tbody>
<tr>
<td>1964</td>
<td></td>
<td></td>
<td></td>
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</tr>
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<td>1984</td>
<td></td>
<td></td>
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<td>2004</td>
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</tr>
<tr>
<td>2025</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Legend:
- Oil
- Coal and carbonized coal
- Renewable energy etc.
- Natural gas
The Combination Scenario
CO2 emissions

The combination scenario

Million tons CO2

'90 '91 '92 '93 '94 '95 '96 '97 '98 '99 '00 '01 '02 '03 '04 2025

Actual
Corrected
The Combination Scenario
Import/export balance

Import and Export of Energy and CO2

- Oil
- Coal
- Natural gas
- Biomass
- Biogas
- Waste
- Electricity
- CO2 (mt)

Reference 2025 PJ
The combi scenario PJ
The Combination Scenario
National economics
Agenda

1. The scenario process
2. The results
3. The modelling tool
   • Energy savings model
   • The time series model
   • The energy flow model
4. Perspectives
The modeling tool: STREAM

• STREAM: Sustainable Technology, Research and Energy Analysis Model
• Simple and transparent model
  – Enhance complete energy flow
  – Developed in cooperation with broad range of parties
  – Conduct new analysis quickly
• Qualify scenarios through quantification
• Give project attendants better insight on the spot in scenario discussions
STREAM

Overall goals (CO2 emissions, fuel use, etc.)

Input
- Production capacity
- Energy service demand
- Conversion factors
- Technological development
- Fuel prices
- Time series (heat, wind and electricity consumption)

STREAM
- Energy savings model
- The time series model
- The Energy flow model

Output
- Energy balance
- Import/export
- Cost calculations (capital, fuel, O&M)
- System efficiency
The energy savings model

- Projection of demand for energy services
  - Calculated for households, service sector, industry and transport
  - In each area different end uses is identified as well as savings potentials and costs
  - Starting point for transport is amount of person kilometres
### The energy savings model

**Regnearksmodel til fremkrivning af efterspørgslen efter endeligt energiforbrug baseret på baggrundstal fra Energistrategien og Energisparesplanen.**

<table>
<thead>
<tr>
<th>Energisparescenario:</th>
<th>“Besparelse Scen1”</th>
<th>Scenerie:</th>
<th>Reference</th>
<th>Kombiscenariat</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anvendt rente ved investeringer:</td>
<td>6%</td>
<td></td>
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</table>

#### Endeligt energiforbrug i sektorer

<table>
<thead>
<tr>
<th>Forbrug</th>
<th>Økonomisk vækst</th>
<th>Intensitet</th>
<th>Ekstra omk.</th>
<th>Ekstra omk.</th>
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</thead>
<tbody>
<tr>
<td>2003</td>
<td>% p.a.</td>
<td>faktor</td>
<td>ifht. basis</td>
<td>ifht. reference</td>
</tr>
<tr>
<td>Basis forbrug</td>
<td>scenario</td>
<td>2025</td>
<td>2025</td>
<td>2025</td>
</tr>
<tr>
<td>Kombiscenariat</td>
<td>scenario</td>
<td>2025</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tj</td>
<td>mill. kr/år</td>
<td>Tj</td>
<td>mill. kr/år</td>
<td>Tj</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
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<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Handel &amp; Service</td>
<td>83.706</td>
<td>1,6</td>
<td>0,75</td>
<td>879</td>
<td>1,184</td>
<td>111.940</td>
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<tr>
<td>Produktion</td>
<td>162.494</td>
<td>1,5</td>
<td>1,00</td>
<td>1.748</td>
<td>2.280</td>
<td>233.304</td>
</tr>
<tr>
<td>Husholdninger, el - rumvarme</td>
<td>186.324</td>
<td>1,9</td>
<td>0,90</td>
<td>3.496</td>
<td>2.734</td>
<td>225.950</td>
</tr>
<tr>
<td>i alt</td>
<td>432.524</td>
<td>6.123</td>
<td>6.524</td>
<td>571.193</td>
<td>413.135</td>
<td>304.411</td>
</tr>
</tbody>
</table>

#### Vækst transportarbejde

<table>
<thead>
<tr>
<th>Årlig besparelse ifht. Basis:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transport, person</td>
</tr>
<tr>
<td>Transport, gods</td>
</tr>
<tr>
<td>i alt inkl. transport</td>
</tr>
</tbody>
</table>

#### Endeligt forbrug fordelt på brændsler (uden transport)

<table>
<thead>
<tr>
<th>Forbrug</th>
<th>Basis forbrug</th>
<th>Reference forbrug</th>
<th>Kombiscenariat forbrug</th>
</tr>
</thead>
<tbody>
<tr>
<td>2003</td>
<td>2025</td>
<td>2025</td>
<td>2025</td>
</tr>
<tr>
<td>El</td>
<td>TJ</td>
<td>TJ</td>
<td>TJ</td>
</tr>
<tr>
<td>Fjernvarme</td>
<td>TJ</td>
<td>TJ</td>
<td>TJ</td>
</tr>
<tr>
<td>Kul</td>
<td>TJ</td>
<td>TJ</td>
<td>TJ</td>
</tr>
<tr>
<td>Olie</td>
<td>TJ</td>
<td>TJ</td>
<td>TJ</td>
</tr>
<tr>
<td>Naturgas</td>
<td>TJ</td>
<td>TJ</td>
<td>TJ</td>
</tr>
<tr>
<td>Biomasse (Enrgiaafgrøder)</td>
<td>TJ</td>
<td>TJ</td>
<td>TJ</td>
</tr>
<tr>
<td>Biomasse (halm,traaafald)</td>
<td>TJ</td>
<td>TJ</td>
<td>TJ</td>
</tr>
<tr>
<td>i alt</td>
<td>432.524</td>
<td>552.824</td>
<td>413.135</td>
</tr>
</tbody>
</table>

* Alle investeringer er omregnet til annualiserede afdrag i 2003-kr. Svarende til lån, der afdrages med samme årlige betaling over investeringens levetid.
The time series model

• Analyse correlations in the Danish electricity and CHP system on an hourly level.

• Indicates coherence between wind and combined heat and power production
The time series model
The time series model

Eforbrugsvarighedskurve - fordelt på segmenter af 500 MW
(Husk: varighedskurven skal opdateres vha. makro)
The energy flow model

• Combine models with economics and technology data for a given year
• Produce tables and figures
• Economic costs is determined as the annual costs of running the system in a given year
# The energy flow model

## Ambitiøse scenario

### Energiprodukter

<table>
<thead>
<tr>
<th>(PJ)</th>
<th>el produktion</th>
<th>fjernvarme</th>
<th>varme/brændsel</th>
<th>Total</th>
<th>el</th>
<th>fjernvarme</th>
<th>olie</th>
<th>kul</th>
<th>naturgas</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>el produktion</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>96,27</td>
<td></td>
<td></td>
<td>96,27</td>
<td></td>
<td>0,96</td>
<td>7,22</td>
<td>9,63</td>
<td></td>
</tr>
<tr>
<td></td>
<td>el, brændselsforbrug</td>
<td>144,60</td>
<td>144,60</td>
<td></td>
<td></td>
<td>1,77</td>
<td>12,67</td>
<td>15,05</td>
<td></td>
</tr>
<tr>
<td>virkningsgrad</td>
<td>67%</td>
<td></td>
<td></td>
<td>67%</td>
<td></td>
<td>54%</td>
<td>57%</td>
<td>64%</td>
<td></td>
</tr>
</tbody>
</table>

| fjernvarme, produktion | 104,83 | 0,04 | 93,05 |          |
| fjernvarme, brændselsforbrug | 66,14 | 66,14 |          |
| virkningsgrad / COP | 159% | 141% |          |

### Produkt

|       | brint, produktion | 0,11 | 0,20 | 0,2   |
|       | ethanol, produktion | 51% | 10,12 | 19,70 | 1,3 | 5,2 |
|       | methanol, produktion | 0% | 0,00 | 0,00 | 0,0 |
|       | biodiesel, produktion | 10,15 | 12,10 | 1,3 | 0,2 |

### Varmeforbrug

|       | 65,42 | 73,75 | 158,54 | 7,18 | 74,51 | 11,80 | 1,83 | 32,36 |

|       | varmeforbrug, brændsel | 89% | 100% | 96% | 90% | 80% | 95% |

|       | nettetab | 6,01 | 20,38 | 0,00 |
|       | egenforbrug | 0,00 |      | 0,00 |      |
|       | Tvangen el-eksport | (0,55) | |
|       | ikke energiformål | 0,00 |      |      |

### El Fjernvarme Summen af Brændsler Total Brændselsforbrug inkl. konverteringstab

<table>
<thead>
<tr>
<th></th>
<th>El</th>
<th>Fjernvarme</th>
<th>Summen af Brændsler</th>
<th>Total</th>
<th>Brændselsforbrug inkl. konverteringstab</th>
</tr>
</thead>
<tbody>
<tr>
<td>Handel og service</td>
<td>20,13</td>
<td>23,90</td>
<td>6,83</td>
<td>50,86</td>
<td>20,13</td>
</tr>
<tr>
<td>Produktionserhverv</td>
<td>36,02</td>
<td>10,87</td>
<td>83,67</td>
<td>130,55</td>
<td>36,02</td>
</tr>
<tr>
<td>Hus holdning</td>
<td>19,86</td>
<td>47,42</td>
<td>55,72</td>
<td>123,00</td>
<td>19,86</td>
</tr>
<tr>
<td>Transport</td>
<td>7,67</td>
<td>146,53</td>
<td>162,45</td>
<td>10,51</td>
<td>5,41</td>
</tr>
<tr>
<td>Forbrug excl. transport</td>
<td>76,02</td>
<td>82,18</td>
<td>146,21</td>
<td>304,41</td>
<td>147,34</td>
</tr>
<tr>
<td>Forbrug</td>
<td>83,68</td>
<td>82,18</td>
<td>292,74</td>
<td>466,86</td>
<td>149,58</td>
</tr>
</tbody>
</table>

### Total bruttoenergiforbrug

|       | 144,60 | 66,14 | 292,74 | 503,48 |

|       | 149,58 | 20,38 | 102,76 |   |

---

**Nota bene:**

- **El:** Electric power
- **Fjernvarme:** District heating
- **Brændsler:** Fuels
- **Virkningsgrad:** Efficiency
- **Cop:** Coefficient of Performance
- **Produktionserhverv:** Production activities
- **Husholdning:** Households
- **Transport:** Transportation
- **Forbrug:** Consumption
- **Bruttoenergiforbrug:** Total energy consumption

---

**Reference:**

- **#REFERENCE!** Indicating missing or incomplete data.
Modelling challenges

• Economic costs from investments and measures handled in a very simple manner

• No economic or advanced optimization of the energy flow and exchange with neighbouring countries.
Origin of data

- Data availability often decisive for modelling
  - Especially in the Energy savings model
- Access to many parties through the scenario process and the active involvement from the politicians
Agenda

1. The scenario process
2. The results
3. The modelling tool
   • Energy savings model
   • The time series model
   • The energy flow model
4. Perspectives
Perspectives

• Consolidation of model
• Public access to modelling tool

• Modelling tool creates common references and understanding of challenges in scenario discussions
  – Also outside Denmark
Vanadium redox-flow batteries
– Installation at Risø for characterisation measurements

Henrik Bindner
Wind Energy Systems
Wind Energy Department
Risø, DTU


Acknowledgement:
The work presented is supported by Energinet.dk through the PSO-project "karakterisering af vanadium batteri"
Presentation outline

• Power system with a high penetration of wind
• Applications of energy storage and energy storage technologies
• Vanadium batteries
• Vanadium battery as part of SYSLAB
• Current Status and test results
Power Systems with high penetration of wind

- Production and consumption has to match at any instant
- Issues with wind
  - Fluctuations
  - Variations
  - Predictability
- The rest of the system has to compensate for the fluctuations on the short time scale (sec-min) and variations and prediction errors on a longer time scale (hours-days)
- Flexibility of the rest of the system is crucial for achieving high penetration
- More and more functions are provided via a market

- Flexibility can be provided by several means
  - Production
  - Flexible/intelligent consumption
  - Energy storage
Power plant functions from wind farms

- Wind turbines are installed in larger and larger wind farms
- The spatial smoothing is reduced resulting in larger fluctuations
- But coordinated control of all the wind turbines is improved

- During recent years there has been an effort to develop functions similar to other power plants to provide frequency and voltage control support
- Due to the stochastic nature of wind it is limited what can be obtained without support technologies
Energy storage functions and issues

- Batteries can have many functions in the power system
- Several of the storage technologies can provide several functions simultaneously
- Potential functions include:
  - Very short term power quality improvement
  - Uninterruptible power supplies
  - Reduction of short term fluctuations in renewable energy production
  - Reduction of spinning reserve
  - Reduction of standing reserve
  - Daily smoothing
  - Seasonal storage
  - Energy arbitrage

- Issues with application of batteries:
  - Costs
  - Uncertainty of cost
    - Lifetime
    - O&M cost
  - Efficiency
  - Self-discharge
  - Operational capabilities
  - Reliability
  - Safety and environmental issues
## Energy storage technology overview

<table>
<thead>
<tr>
<th>Technology</th>
<th>Power/Energy Range</th>
<th>Applications</th>
<th>State of development</th>
</tr>
</thead>
<tbody>
<tr>
<td>Supercapacitors, superconducting magnetic energy storage</td>
<td>High power Low energy</td>
<td>UPS, power quality</td>
<td>Pre-mature</td>
</tr>
<tr>
<td>Flywheels</td>
<td>High Power Low Energy</td>
<td>Power quality</td>
<td>Mature</td>
</tr>
<tr>
<td>Batteries: lead acid, lithium, natrium-sulphur, nickel</td>
<td>Medium power Medium Energy</td>
<td>UPS, RE fluctuation reductions</td>
<td>Pre-mature – mature</td>
</tr>
<tr>
<td>Redox-flow batteries: Vanadium, Br-S, Zn-Br</td>
<td>Medium power High Energy</td>
<td>RE fluctuation reduction,  spinning/standing reserve</td>
<td>Pre-mature</td>
</tr>
<tr>
<td>Pumped hydro</td>
<td>High Power Very High Energy</td>
<td>Spinning/standing reserve, energy arbitrage</td>
<td>Mature</td>
</tr>
<tr>
<td>Compressed air</td>
<td>High Power Very High energy</td>
<td>Spinning/standing reserve, energy arbitrage</td>
<td>Mature</td>
</tr>
<tr>
<td>Hydrogen</td>
<td>Medium Power High Energy</td>
<td>RE fluctuation reduction,  spinning/standing reserve</td>
<td>Prototype</td>
</tr>
<tr>
<td>Thermal</td>
<td>-</td>
<td>RE fluctuation reduction,  spinning/standing reserve</td>
<td>Mature</td>
</tr>
<tr>
<td>Demand response</td>
<td>-</td>
<td>RE fluctuation reduction,  spinning/standing reserve</td>
<td>Pre-mature</td>
</tr>
</tbody>
</table>
Vanadium redox-flow battery technology

- Flow/membrane based battery
- Electrolyte is vanadium dissolved in sulphuric acid
- Electrodes do not participate in the electro-chemical process
- Same electrolyte on both sides
  - No cross-contamination
  - Very long lifetime
- Independent sizing of power and energy capacity
- Low maintenance
- Very good cycling capability – more than 10000 cycles
- Good efficiency ~75%
- Low self-discharge
- Fast response

Only change in valence of vanadium

\[
\begin{align*}
V^{4+} &\rightarrow V^{5+} + e^- \\
V^{5+} + e^- &\rightarrow V^{4+}
\end{align*}
\]

Charge

\[
\begin{align*}
V^{3+} + e^- &\rightarrow V^{2+} \\
V^{2+} &\rightarrow V^{3+} + e^-
\end{align*}
\]

Discharge
Vanadium flow battery

- Current costs:
  - 250kW/2MWh:$1,000,000
- Potential for lower cost if mass-produced

- Energy density:
  - ~25Wh/kg
- Risø unit:
  - 15kW/120kWh
  - 4 quadrant power electronics
  - Island and grid connected mode of operation
Component testing – Characterisation of vanadium batteries

- PSO-project – supported by Energinet.dk
- Hands-on experience
- Efficiency @ different operating conditions
- Response time etc.
- Limits for operating range
- Cycling ability
- Grid interface
High penetration wind power systems

- Intelligence/Communication
  - Embedded, distributed control
- Self-organising distributed control
- Flexibility
  - FlexHouse, Demand response
  - Vanadium battery
  - Hybrid/Electric car
SYSLAB – Development perspectives

• Investigate technical possibilities
  • Embedded intelligence
  • Distributed control
  • Integration of energy carriers
  • Multiple RE sources
• Possible extensions
  • Hydrogen/Fuel cells
  • Biomass
  • Risø district heating/houses

• Integrates several areas of research
• Upscaling to nationwide system
  • Simulations (IPSYS)
• Facility used in PhD and MSc projects

1-5 kW Topsoe FC CHP Test System
Electrical layout of SYSLAB

- Flexible grid configuration
- Autonomous grid
- Units can be tested in under various grid conditions
- Suitable for component and system tests
- Very flexible control
PowerFlexhouse

- Intelligent control
- Demand response
- Many individually controllable loads
  - Heater
  - Airconditioners
  - Water heater, coffee machine
- Many sensors
- System-house and house-user interaction and communication
- Plug-in/vehicle2grid hybrid car: Toyota Prius with extended battery and bi-directional converter
Vanadium redox-flow batteries – initial results

- Unit will be installed in August 2007
- Unit is being factory tested

- Foot-print is 7mx7m
- Tanks are 8m$^3$ each
Factory test of system

- 3*kW cells stacks
- 15kW/20kVA power electronics
Factory tests II

- Energy %
- Tank Temp Deg C
- Pcs1_Pac
- Pcs1_Pbat
- Temp

20070508
Factory test III

- Cycling test
Factory test IV

- Single charge-discharge cycle
Demonstration of the SYSLAB facility

- Everyone is welcome at SYSLAB after the conference
- The SYSLAB will be demonstrated and there will be time for discussions
- See you at the center of the RED circle (Møllehallen)
Centralised and decentralised control – a power system point of view

Oliver Gehrke (Risø/DTU)
Stephanie Ropenus (Risø/DTU)
Philippe Venne (UQAR)
Outline

1. Requirements and challenges for current power systems
2. Design parameters for power system evolution
3. Decentralised control
4. Activities at Risø
Demands for future power systems

- Integration of distributed generation
- Integration of intermittent energy sources
- Markets for power and ancillary services
- Open, equal and barrier-free access for third-party service providers
- Security of supply
- Power quality
- Energy efficiency
Limitations and challenges in current systems

- Growing complexity, bad scalability
- Limited access to power markets
- Lack of data and automation in large parts of the grid
- Lack of flexibility: Power system structure is considered static in the short and medium term
- DG *needs* to provide ancillary services, because their peak contribution grows faster than their average contribution
- Large untapped potential for demand response (households, refrigerated warehouses, greenhouses etc.)
- Lack of transmission capacity
Not a simple evolution in one area of technology. Many aspects and design parameters and no general agreement on the target.

- Role of small DER and households
- Types of markets for power and ancillary services
- Market access rules and regulation
- Communication
- Topology of distribution grids
- Role of storage technologies
- Role and providers of ancillary services
- Role of the system operator and its control center

Big differences in current implementations, under technological, economical and political aspects.
Use of communication technology

- Dedicated (private) communication links between control center and larger units
- One-way broadcasts to smaller units
- Two-way communication with DER at the household level, using public infrastructure
- Communication protocols beyond SCADA (policies, negotiation etc.)
Small DER interaction

- Meter read once a year
- Real-time metering and price signals (user-in-the-loop)
- Automated demand response
- Direct participation in market mechanisms (power and ancillary services)
Market access

- Easier access
  - High thresholds (capacity requirements, trading fees)
  - Market aggregators allowed
  - Open access to markets or sub-markets
System control and operation

- Control Center
- Aggregation (Virtual Power Plants)
- Delegation (Services provided by grid)
- Self-organisation

Increasingly decentralised
Design parameters are mutually dependent, but not always strongly linked.

Example: Market access for small DER requires some form of communication, but not all types of communication link make sense economically.

Many possible scenarios, picking a particular one is speculative.

The way of operating and controlling the power system is a central issue. It is not clear what is technically possible.
Decentralised operation and control

- Reducing complexity by solving local issues locally, with local data
- Better scalability, making future DER technologies less disruptive
- More flexibility when responding to changes in system structure
- Eliminating single points of failure
- Need for widely available protocols and interfaces promotes accessibility
Vision for a future power system (2025+)

- Grid is self-aware (knows its topology, capabilities, limits and state)
- Role shift: System operator-> System facilitator
- “Human-out-of-the-loop”: Supervisors set policies, rather than execute them.
- Flexible, negotiated control hierarchies
- Boundaries between transmission and distribution system become blurred
- Wide-scale use of automated demand response at the household level
- Use of public communication networks (Internet) for small-size DER
- Open – and largely automated - access to markets for power and ancillary services
- New services: Self-islanding, dynamic protection management
Generic architecture for a decentralised power system

- **Device**: Grid-connected energy resource
- **Device representative**: Logical unit providing access to a device
- **Device representative controller**: Supervises one or more devices
- **Distributed controller**: Composed of individual controllers
“Playground” implementation: SYSLAB

Not feasible to test in a real power system (not at this stage) and no tools available for the combined simulation of
- power system dynamics
- stochastic communication systems
- real-time decentralised decision making

Possible approaches:
- Use a small experimental power system (accepting that scaling issues are postponed)
- Use a real-time grid simulator with real-world controllers (accepting that interfacing issues are postponed)

Advantages of an experimental system:
- Most realistic control system studies
- Results have more convincing power
- Advanced environment for component testing
- One intelligent node per power system component
- Local data acquisition and storage
- Development of self-organising middleware for “plug-and-play” operation
- Supervisory control shared between nodes

Purpose: Testing of communication protocols, control algorithms, energy technologies and components, human-machine interaction
Assessing the Role of Energy in Development and Climate Policies in Large Developing Countries

Amit Garg and Kirsten Halsnæs

Risø International Energy Conference 2007
24 May 2007
How to align sustainable development, energy and climate change policies at national level (for Brazil, China, India and South Africa)?

What are sustainable development indicators and their future projections that capture the above alignments?

What are the CO₂ and local pollutant emissions implications of development under a reference scenario for these countries?

Can alternative development pathways align energy and climate change policy perspectives, and how?
Development, Energy and Climate Project
Methodology

• Used integrated energy modelling framework
• Each country uses comparable energy-environment models
• Consistent reference scenario assumptions in line with global climate change scenario efforts
• Consistent assumptions on oil and gas prices, UN population projections
• National case studies conducted and up scaled to integrate with country models
Human activities and most sustainability issues are closely linked to energy use

• Critical component in factor productivity (capital, labor, land), can constrain well being, missing energy imposes time and labor burden on households

• Most important sustainability issues (poverty alleviation, health, education, economic development) as well as climate change issues directly relate to production and use of energy

• Even some of the other important sustainability issues (freshwater, landuse, atmospheric integrity, agriculture) are directly/indirectly related to production and use of energy

World (humans, systems and environment) can be easily visualized as a flow of and linked through energy
Why Use an Integrated Energy Framework? (contd.)

- Offers consistent, comparable and transparent framework for future projections
  - Relationships between sustainability dimensions are considered consistently
  - Can project and compare across alternative development pathways
  - Can compare across different countries (if due care is taken)
  - Can compare SD and CC impacts of competing technologies

- Possible to estimate future energy flows and most of the proposed indicators with commonly used energy models
  - Economic models miss out on environmental issues such as climate change
  - Environmental models miss out on macro-economic depth and are very sector/region specific
## Modeling SD, Energy and CC Linkages

<table>
<thead>
<tr>
<th>Millennium development goals and global targets</th>
<th>India’s national development targets</th>
<th>Energy sector implications</th>
<th>Implications for energy modeling</th>
</tr>
</thead>
</table>
| **Goal 1: Eradicate extreme poverty and hunger**<br>**Target 1:** Halve, between 1990 and 2015, the proportion of people whose income is less than $1 a day<br>**Target 2:** Halve, between 1990 and 2015, the proportion of people who suffer from hunger | • Double the per capita income during 2002-2012  
• Reduction of poverty ratio by 5 percentage points during 2002-2007 and by 15 percentage points during 2002-2012  
• Reduce decadal population growth rate to 16.2% between 2001–2011 (from 21.3% during 1991–2001) | • Energy for increased production and consumption  
• Energy for local enterprises and machinery  
• Energy and electricity to facilitate income generation  
• Energy for providing family planning and health services | • GDP and population projections  
• Sectoral demand projections consistent with the above  
• Reflect/capture inputs needed for increased health services etc in sectoral demand projections  
• Energy needed for the above using sectoral/ national models |
Using energy framework for SDI requires an approach where the energy analysis starts with development and human needs rather than structured around energy system logics.

- **Economic indicators**
  - Efficiency of production indicators
  - Efficiency of energy use indicators
  - Energy investment indicators

- **Environmental indicators**
  - GHG and local pollutant emissions (per unit of output and per capita)
  - Share of solid fuels in residential sector (households)

- **Social indicators**
  - Energy affordability indicators
  - Per capita consumption
  - Share of clean energy in residential sector (households)
Integrated Energy Modeling and SDI

Useful energy delivery

- Heating and cooling
- Lighting
- Mechanical work
- Electricity (for health, ICT etc), Chemical and other energy forms, etc.

Final energy service delivery

<table>
<thead>
<tr>
<th>Sectors</th>
<th>End-use energy consumption</th>
</tr>
</thead>
<tbody>
<tr>
<td>Residential (households)</td>
<td></td>
</tr>
<tr>
<td>Industry</td>
<td></td>
</tr>
<tr>
<td>Transport</td>
<td></td>
</tr>
<tr>
<td>Services and commercial</td>
<td></td>
</tr>
<tr>
<td>Agriculture</td>
<td></td>
</tr>
</tbody>
</table>

Energy consumption for economic activities

Energy production

<table>
<thead>
<tr>
<th>Conversion process</th>
<th>Technology-fuel matrix</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electricity generation</td>
<td></td>
</tr>
<tr>
<td>Oil refining</td>
<td></td>
</tr>
<tr>
<td>Solid fuel production</td>
<td></td>
</tr>
</tbody>
</table>

Energy extraction and conversion

Naturally occurring energy resources

- Biomass, fossil fuels (coal, crude oil, natural gas), hydro, nuclear, solar, wind, others

Human well-being, poverty, equity indicators

- Share of clean energy (fuels and/or technologies) in residential sector
- Per capita power and/or energy consumption
- Household power and/or energy (cleaner) access
- Price of energy and/or power, share of energy in HH monthly expenditure

Resource conservation indicator

- Ratio of primary renewable energy to total primary energy supply (TPES)

Linkages with relevant SDI

Energy flows
Some Cross-country Results
## Energy Policies Linked with SD and CC

<table>
<thead>
<tr>
<th><strong>China</strong></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>2004</strong></td>
<td>60 GW renewable power capacity by 2010 (10% of total power generating capacity) and 121 GW by 2020 (12% of total capacity)</td>
</tr>
<tr>
<td><strong>2005</strong></td>
<td>Medium-Long term Energy Conversation programme, annual energy conservation rate of 2.2% till 2020 covering various sectors.</td>
</tr>
<tr>
<td><strong>Current</strong></td>
<td>Strong economic growth, and declining population growth</td>
</tr>
<tr>
<td><strong>Current</strong></td>
<td>More efficient coal-based power generation from existing and new plants</td>
</tr>
<tr>
<td><strong>Current</strong></td>
<td>Strong thrust on energy efficiency improvement in all sectors (e.g. 20% energy intensity reduction during 2005-2010, efficiency of coal-fired power plants to increase to 40% by 2030, new building to reach 75% increase standards in 2030 etc.)</td>
</tr>
<tr>
<td><strong>UC</strong></td>
<td>Nuclear power capacity of 40 GW by 2020</td>
</tr>
</tbody>
</table>
### Energy Policies Linked with SD and CC

<table>
<thead>
<tr>
<th>Year</th>
<th>Policy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current</td>
<td>More efficient coal-based power generation from existing and new plants</td>
</tr>
<tr>
<td>2001</td>
<td>reduce power transmission and distribution losses</td>
</tr>
<tr>
<td>2002</td>
<td>10% of new power generation capacity by renewables by 2012</td>
</tr>
<tr>
<td>2002-Current</td>
<td>Doubling per capita income during 2002-2012, and to reduce decadal population growth rate to 16.2% between 2001-2011 (from 21.3% during 1991-2001)</td>
</tr>
<tr>
<td>2002</td>
<td>Auto fuel policy: Emission norms for new vehicles - Euro-3 equivalent norms from 2010 for the entire country, but for 11 large cities Euro-3 equivalent from 2005 and Euro-4 equivalent from 2010</td>
</tr>
<tr>
<td>2005</td>
<td>Ethanol blend in gasoline (up to 5-10% in phases), ongoing discussions for expansion</td>
</tr>
<tr>
<td>2005</td>
<td>100% household electrification in rural areas by 2010 covering 75 million rural households, and modernizing rural electricity infrastructure</td>
</tr>
<tr>
<td>2006</td>
<td>Minimum employment guarantee scheme for rural areas (100 days’ employment per household per year) in 200 districts (extended to 350 districts now)</td>
</tr>
<tr>
<td>UC</td>
<td>Nuclear power capacity of 20 GW by 2020</td>
</tr>
</tbody>
</table>
Efficiencies of Energy Use

- GDP becomes less energy and less CO₂ intensive under all scenarios
- Decoupling rates, timings and extent are however different for different countries
- Sectoral variations exist in each country
Decoupling of Energy and CO$_2$ Emissions

- Energy and CO$_2$ emissions do not decouple much under reference scenario
- Reasons are different for each country
• Large developing countries are projected to add considerable fossil fuel based capacities during 2007-2030

• CO₂ emissions are projected to grow as a result
• CO₂ and local pollutant emissions (e.g. SO₂, NOₓ and particulates) decouple.

• Elasticity of mitigating CO₂ as a side-benefit of SO₂ mitigation policy is lower (0.1-0.01 in 2020 for India) than elasticity of mitigating SO₂ as a side-benefit (1.2 to 1.4 in 2020 for India) from a direct CO₂ mitigation policy. Same for CO₂ and particulates. Similar trends for China.

• Policy relevance and investment implications.
SD Indicators Linked with the Power Sector
• Current efficiency of production is relatively lower, however projected to improve in future.

• China, India and South Africa consume over 40% of global coal, about 2/3\textsuperscript{rd} is for power generation.
Average CO₂ emissions per unit of electricity generated are much higher than the best global practices.
General Conclusions about the Relationship between Development and Energy

• Reallocation of household time (especially by woman) from energy provision to improved education and income generation and greater specialisation of economic functions.
• Economics of scale in more industrial-type energy provision.
• Greater flexibility in time allocation through the day and evening.
• Enhanced productivity of education efforts.
• Greater ability to use a more efficient capital stock and take advantage of new technologies.
• Lower transportation and communication costs.
• Health related benefits: reduced smoke exposure, clean water and refrigeration.
## Households

<table>
<thead>
<tr>
<th>HH income category</th>
<th>India rural, 2000</th>
<th>India urban, 2000</th>
<th>China urban, 2004</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Absolute expenditure (USD, 2000 prices)</td>
<td>% share of total HH expenditure</td>
<td>Absolute expenditure (USD, 2000 prices)</td>
</tr>
<tr>
<td>Poorest 0-5%</td>
<td>0.46</td>
<td>10.2%</td>
<td>0.65</td>
</tr>
<tr>
<td>0-10%</td>
<td>0.51</td>
<td>10.1%</td>
<td>0.80</td>
</tr>
<tr>
<td>10-20%</td>
<td>0.62</td>
<td>9.0%</td>
<td>1.04</td>
</tr>
<tr>
<td>20-40%</td>
<td>0.73</td>
<td>8.7%</td>
<td>1.46</td>
</tr>
<tr>
<td>40-60%</td>
<td>0.97</td>
<td>8.9%</td>
<td>1.73</td>
</tr>
<tr>
<td>60-80%</td>
<td>1.15</td>
<td>8.6%</td>
<td>2.13</td>
</tr>
<tr>
<td>80-90%</td>
<td>1.44</td>
<td>8.1%</td>
<td>2.67</td>
</tr>
<tr>
<td>Top 90-100%</td>
<td>1.79</td>
<td>7.2%</td>
<td>4.01</td>
</tr>
</tbody>
</table>
### Table 2 Summary of How a Typical Household in Rural Philippines Benefits from Electricity, 1998

<table>
<thead>
<tr>
<th>Benefit Category</th>
<th>Benefit Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Less expensive and expanded use of lighting</td>
<td>36.75 US $</td>
<td>Household</td>
</tr>
<tr>
<td>Less expensive and expanded use of radio and television</td>
<td>19.60 US $</td>
<td>Household</td>
</tr>
<tr>
<td>Improved returns on education and wage income</td>
<td>37.07 US $</td>
<td>Wage earner</td>
</tr>
<tr>
<td>Time savings for household chores</td>
<td>24.50 US $</td>
<td>Household</td>
</tr>
<tr>
<td>Improved productivity of home business</td>
<td>34.00 (current business)</td>
<td>Business</td>
</tr>
<tr>
<td></td>
<td>75.00 (new business)</td>
<td></td>
</tr>
</tbody>
</table>

Source: ESMAP, 2002 Table E-1
• Reducing energy poverty, and enhanced electricity access for developmental goals is projected to increase electricity requirements during 2007-2030

• Coal based power is projected to remain the primary source - mainly due to energy security considerations

• Coal use becomes cleaner, but not clean enough.
Sustainable Development Indicators for China

- HH electricity access
- Per capita electricity
- Efficiency of electricity generation (fossil)
- Investments in new power plants
- Renewable share in power generation

Indicators:
- SO2/TPES
- TPES/GDP
- CO2/GDP
- CO2/TPES
- Efficiency of electricity generation (fossil)
- Per capita electricity
- Investments in new power plants
- Renewable share in power generation

Years:
- 2000
- 2010
- 2020
- 2030
Cross-country SDIs

China
- HH electricity access
- Per capita electricity
- Efficiency of electricity generation (fossil)
- Investments in new power plants
- Renewable share in power generation

India
- HH electricity access
- Per capita electricity
- Efficiency of electricity generation (fossil)
- Investments in new power plants
- Renewable share in power generation

South Africa
- HH electricity access
- Per capita electricity
- Efficiency of electricity generation (fossil)
- Investments in new power plants
- Renewable share in power generation

Brazil
- HH electricity access
- Per capita electricity
- Efficiency of electricity generation (fossil)
- Investments in new power plants
- Renewable share in power generation
National Energy Case Studies of Climate Friendly Development
### National Success Stories for China and India

<table>
<thead>
<tr>
<th>Case example</th>
<th>Development impacts</th>
<th>Climate change mitigation/adaptation</th>
</tr>
</thead>
<tbody>
<tr>
<td>China:</td>
<td>Local air pollution control, Energy cost savings in efficiency cases</td>
<td>Total SD scenario offers CO₂ reductions of 1.5 billion tC in 2030</td>
</tr>
<tr>
<td>Energy efficiency in industry and power production</td>
<td></td>
<td></td>
</tr>
<tr>
<td>India:</td>
<td>Energy supply savings, cost savings, CO₂ and SO₂ emission reductions</td>
<td>1.4 billion tC and 50 million ton SO₂ saved over 30 years, Flood control, Reduced energy/electricity costs</td>
</tr>
<tr>
<td>South Asia energy-electricity market integration</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
## National Success Stories for Brazil

<table>
<thead>
<tr>
<th>Case examples</th>
<th>Development impacts</th>
<th>Climate change mitigation/adaptation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ethanol programme</td>
<td>Employment, foreign exchange savings, local air pollution</td>
<td>9.45 MtC saved per year (17% of energy sector emissions in 1994)</td>
</tr>
<tr>
<td>Zero tillage to ensure higher content of organic matters in soil</td>
<td>Increased use of herbicides, energy cost savings</td>
<td>60-80 Mt CO₂ not released in 1999, 70% reduction in diesel consumption</td>
</tr>
</tbody>
</table>
### National Success Stories for South Africa

<table>
<thead>
<tr>
<th>Case examples</th>
<th>Development impacts</th>
<th>Climate change mitigation/adaptation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clean energy generation mix: Gas, hydro, renewables, nuclear</td>
<td>Energy security benefits, local environmental improvements</td>
<td>Annual CO₂ savings in 2025: 70 Mt CO₂</td>
</tr>
<tr>
<td>Industrial energy efficiency in 3 major companies</td>
<td>Energy cost savings, local environmental benefits</td>
<td>Annual CO₂ savings of around 0.07 mtCO₂</td>
</tr>
</tbody>
</table>
Analysing Alternative Pathways for Aligning SD, Energy and CC
Points of Intervention

• Business-As-Usual energy policies will not change the development path to a desirable climate friendly pathway

• We need to intervene at critical times (starting now) and through appropriate policies to change the development (and therefore emission) pathways

• These Points of Intervention could be, e.g.
  ➢ Bringing in cleaner coal technologies for power generation
  ➢ Biofuels
  ➢ Rural electrification
  ➢ Efficient transport (e.g. strengthening railway networks including metros)
  ➢ Dematerialization of product designs at all levels
  ➢ Cleaner fuels/technologies for cooking
  ➢ Environmental education and consciousness at all levels
## Alternative Developmental Pathways for India: Comparative Performances

<table>
<thead>
<tr>
<th>Parameters</th>
<th>IA1</th>
<th>IA2</th>
<th>IB1</th>
<th>IB2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Global equivalent scenarios</td>
<td>Fossil intensive</td>
<td>Markets first</td>
<td>Global sustainability</td>
<td>regional solutions</td>
</tr>
<tr>
<td>GDP annual growth (2000-2030)</td>
<td>7.1%</td>
<td>5.5%</td>
<td>6.5%</td>
<td>4.2%</td>
</tr>
<tr>
<td>Cumulative Bt-CO₂ (2000-2030)</td>
<td>61</td>
<td>53</td>
<td>45</td>
<td>23</td>
</tr>
<tr>
<td>Per capita CO₂ in 2030 (ton-CO₂)</td>
<td>2.3</td>
<td>1.8</td>
<td>1.7</td>
<td>1.4</td>
</tr>
</tbody>
</table>
Mitigate 8 Bt-CO₂ over 2000-2030 to transit from IA2 (Markets first) to IB1 (Global sustainability) pathway

Welfare loss due to;
- Mitigation costs (up to 1.5% GDP loss)
- Other development paradigms and GDP follow IA2 scenario (and not IB1)

Better to follow climate friendly development path from the beginning
## Clean Coal Technologies in China Under Alternative Pathways

<table>
<thead>
<tr>
<th>Sector</th>
<th>Technology</th>
<th>Share in 2030</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Reference scenario</td>
</tr>
<tr>
<td>Power generation</td>
<td>Super Critical</td>
<td>25%</td>
</tr>
<tr>
<td>Power generation</td>
<td>IGCC</td>
<td>4%</td>
</tr>
<tr>
<td>Industry/Boiler</td>
<td>Advanced boiler</td>
<td>45%</td>
</tr>
<tr>
<td>Industry/Kiln</td>
<td>Advanced kiln</td>
<td>38%</td>
</tr>
<tr>
<td>Coal processing</td>
<td>Coal liquefaction</td>
<td>2% of total coal</td>
</tr>
<tr>
<td>Desulphurization in power plants</td>
<td></td>
<td>58% of all plants</td>
</tr>
</tbody>
</table>
Policy impacts on development, energy and climate change:

• Energy security

• Large employment to low income families that are employed with the production of the technologies (7.6 million people in 2004 and 7.8 million people in 2030)

• Establishment of a strong position for China on international markets for cleaner coal technologies

• Reduction in local and global emissions
Key Lessons Learnt

- BAU energy policies of large developing countries will not align their national developmental goals with global climate change mitigation concerns
- Integration of climate and broader SD concerns early in energy policy process (path change) is cost-effective both from development and climate change perspectives
- Each country has to choose its own development pathway. Diversity of alternative opportunities, projects and approaches exist
- National case studies demonstrate that many dedicated development policies and activities make ("unintended") positive climate contributions
- Quantifying development and climate change impacts of energy policies enhances policy relevance of the research considerably
- The ‘non-climate’ route for international climate change policy making is feasible and cost-effective
- Main challenge is implementation
Thanks
Sustainable Transport Practices in Latin America

Energy Solutions for Sustainable Development

Jorge Rogat and Miriam Hinostroza
UNEP Risø Centre
Roskilde, Denmark
The Transport Situation in Latin America

- Lack of efficient, reliable and safe public transport systems
- Excessive number of old, unsafe and highly polluting buses
- Deregulated sector
- Lack of resources and political will
- Steadily increasing private motorisation in the region (250% increase in the car fleet between 1970 and 1990)
- Increased congestion, number of accidents and air pollution
The turning point

- Need to reformulate transport policies with the aim of providing safe, cost-effective, and environmental-friendly public transport systems

- Curitiba in Brazil became the first city in Latin America to rethink transport policies and found in integrated urban planning and mass rapid transit, with BRT (Bus Rapid Transit) as the main component, the answer to the problem
• The example was first followed by Bogota, Colombia with the implementation of Transmilenio

• Today BRT systems have been implemented, or are in the implementation phase in Guayaquil, Ecuador; Guatemala City, Santiago, Chile and other LA cities
• BRT systems have been implemented or are planned in Jakarta, Indonesia; Beijing, China; Bangkok, Thailand; Nantes, France, Eindhoven, Netherlands; Boston and Orlando in the USA; Adelaide, Australia

• Unique example of South-South, South-North technology transfer

**Definition of BRT**

is a system that emphasises priority for rapid movement of buses by securing segregated busways (IEA, 2002)
How do BRT systems work?

- In a similar way to light-rail trains or rail-based metros, but operate along corridors on dedicated busways at street level
- Use articulated buses with a carrying capacity of around 160 passengers or bi-articulated buses (270 passengers)
- Supplemented by feeder buses
- Modal integration complementing other transport systems
- Can carry up to 35,000 passengers per hour in a direction
- Rapid boarding
- Public-private partnership
Successful practices

Curitiba’s Integrated Transport Network (ITN)

• Integrates land use and public transport under joint public-private operation with emphasis on equity and affordability

• Government officials started in the 60s to work on a master plan

• Restructured the city’s radial configuration into a linear model of urban expansion
- Three-part road system with each axis made up of a central street with special lanes for efficient public transportation

- In 1971 Jaime Lerner developed plans for the ITN of Curitiba

- Favouring public transport, using appropriate rather than capital-intensive technologies
In 1974 the first BRT system in Latin America was operational

- Thirteen express routes with direct routes using boarding tubes
- Twenty eight routes including special buses for students and the disabled
- Approximately 1900 buses of which 500 articulated buses (160) and 300 bi-articulated buses (270) that carry around 2 million passengers/day or about 75% of the total number of passengers
Around 58 km of dedicated busways along 5 corridors complemented by 270 km of feeder routes and 185 km of inter-district routes.

Feeder and inter-district routes supplemented by city centre routes.

Prepaid boarding (one ticket) through 25 transfer terminals and 221 tube stations.
Curitiba
Bogota’s Transmilenio

- With Curitiba as the source of inspiration, but taking into consideration prevailing local conditions

- More because of the chaotic transport problem affecting the mega city than the aim of urban development as in the case of Curitiba

- A component of the city’s Mobility Strategy
• To provide an efficient, safe and comfortable mass rapid transit system for the people

• With emphasis on affordability meaning: (1) possible for the government to afford the infrastructure; (2) for the private sector to recover costs of bus acquisition and operations and; (3) for the users to pay the fare
Transmilenio was launched in December 2000

- The BRT system is currently composed of about 800 articulated buses and 470 feeder buses

- Covers about 400 km along 22 dedicated busways with 2 lanes in each direction

- Carries up to 45 thousand passengers per hour and direction

- Managed by public-private partnership

- It aims at transporting 80% of the people of Bogotá by 2015
Transmilenio
Some of the new initiatives

Guayaquil’s Metrovía

• Metrovía is the main component of the Massive Urban Transport (MUTP) Programme of Guayaquil

• Like in Bogotá it is thought to be the answer to the problems affecting the transport sector

• The main objective of the MUTP is to provide an efficient, safe, reliable, fast and affordable public transport system to the 84% of the population using public transportation
The first corridor introduced in August 2006

- Uses 72 articulated buses and 69 conventional buses as feeder buses
- It’s expected to carry 140 thousand passengers per day
- Prepaid boarding
- Managed by a public-private partnership
- When the complete BRT is in place (2020), 7 corridors will be operational
Metrovía
Guatemala City’s Transmetro

- First replication of Curitiba and Transmilenio in Central America
- Main component of the Urban Mobility Plan for 2020
- Main objective to provide reliable, safe and affordable transport services for the people
- To decrease congestion, vehicle operational costs, travel time, traffic accidents, energy consumption and local air pollution
- Transmetro is considered key in achieving these objectives
First corridor operational in February 2007

- Managed by a public-private partnership

- New and cleaner articulated buses with a carrying capacity of 160 passengers (48 articulated buses of which 17 are new)

- Replace 4-5 old buses by a new bus

- The system is expected to transport 180 thousand passengers per day

- When completed in 2020 it will be composed of 12 corridors
Transmetro
Santiago’s Transantiago

• One of the components of a comprehensive restructuring of the whole public transport sector designed by the government of Chile in 1995

• Main objectives are: (1) to solve the current transport problems; (2) to maintain the current 50% ridership; (3) to provide a reliable and safe public transport system and; (4) to develop a modern, environmentally clean and economically efficient public transport system

• Is being implemented by various ministries

• When completed will consist of 5 corridors
Transantiago was launched in February 2007

- It has been integrated with the Metro and with urban and interurban trains

- It uses around 4,700 buses (1,200 new buses) including articulated and conventional feeder buses instead of 7,500 used before

- Feeder buses complement both the BRT and the Metro

- Fare collection through smart electronic prepaid cards

- Fare depending on the numbers of transfers made but with a maximum fare of US$0.80
Results

Curitiba’s ITN

- 30% previously travelled by car
- 27 million fewer trips made by car
- per capita fuel consumption has decreased by 30%
- air pollution is the lowest in the country
Transmilenio

- 90% fewer traffic accidents
- about 40% less air pollution
- 40% reduction in travel time
- 90% passenger satisfaction
Metrovía

• High passenger satisfaction

• 97% on-time performance on both trunks and feeders

• Increased travel speed from 16 to 22km
Transmetro

- High passenger satisfaction
- Increased safety
- 80% reduction in travel time
Transantiago

- Extremely low passenger satisfaction
- Increased travel time (20 to 30 minutes)
- The Metro has collapsed
Conclusions

• Well planned and implemented BRT systems have proven to be the right transport solution in many cities

• BRT systems can provide high quality services similar to other MRT systems like light-rail trains or metro

• High political will reflected in continued local transport policy aimed at favouring the use of public transport

• Urban planning compatible with innovative public transport solutions
• Appropriate rather than capital-intensive technology:
  BRT cost/km 2 – 5US$ million while rail based metro 60 - 200US$ per km

• Participatory approach

• Gradual changes in passengers’ habits
Environmental Analysis of Coal-based Power Production with Amine-based Carbon Capture

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J. Nazarko², A. Schreiber¹, P. Zapp¹

Institute of Energy Research
1 Systems Analysis and Technology Evaluation (IEF-STE)
2 Fuel Cells (IEF3)
Forschungszentrum Jülich GmbH
Outline

1. Introduction
2. CO₂ capture concepts
3. Methodology and basic parameters
4. Inventory analysis
5. Impact assessment
6. Summary and outlook
Introduction

- Increase of future global electricity demand
- Strong dependency on fossil-based power generation (coal, gas)
- Increasing share of renewable energies
- Decreasing share of nuclear power and hydropower

- Increasing global CO₂ emissions
- Share of CO₂ from transport increasing
- Share of CO₂ from industry and households decreasing
- Share of CO₂ from power generation increasing, unless measures like CCS are taken

• Worldwide investment in fossil-based power generation capacity expected
• European Union: Announced construction of new plants
• Coal and gas power generation in Germany: 27 announcements of new power plants (coal, lignite), 25,000 MW

(Source: Handelsblatt, VDEW, BUND)
## CO₂ capture concepts

<table>
<thead>
<tr>
<th>Concepts</th>
<th>Energy supply perspective: Assets (+) and drawbacks (-)</th>
<th>Environmental impacts: Assets (+) and drawbacks (-)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Post combustion:</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CO₂ capture from flue gas</td>
<td>+ technology available</td>
<td>+ reduced net CO₂ emissions</td>
</tr>
<tr>
<td></td>
<td>+ retrofitting possible</td>
<td>? process inputs</td>
</tr>
<tr>
<td></td>
<td>- high energy penalty</td>
<td>? process outputs</td>
</tr>
<tr>
<td></td>
<td>- high cost increase</td>
<td></td>
</tr>
<tr>
<td></td>
<td>? process inputs</td>
<td></td>
</tr>
<tr>
<td></td>
<td>? process outputs</td>
<td></td>
</tr>
<tr>
<td><strong>Oxyfuel:</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CO₂ concentration in flue gas</td>
<td>+ compact boiler design</td>
<td>+ reduced net CO₂ emissions</td>
</tr>
<tr>
<td></td>
<td>+ high retention rates</td>
<td>? process inputs</td>
</tr>
<tr>
<td></td>
<td>- high e-penalty for air sep.</td>
<td>? process outputs</td>
</tr>
<tr>
<td></td>
<td>- high invest cost</td>
<td></td>
</tr>
<tr>
<td></td>
<td>? process inputs</td>
<td></td>
</tr>
<tr>
<td></td>
<td>? process outputs</td>
<td></td>
</tr>
<tr>
<td><strong>Pre combustion:</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CO₂ capture from syngas after</td>
<td>+ lower e-penalty</td>
<td>+ reduced net CO₂ emissions</td>
</tr>
<tr>
<td>CO-shift</td>
<td>+ hydrogen production</td>
<td>? process inputs</td>
</tr>
<tr>
<td></td>
<td>- technical availability of IGCC</td>
<td>? process outputs</td>
</tr>
<tr>
<td></td>
<td>- complex CO₂ capture</td>
<td></td>
</tr>
<tr>
<td></td>
<td>? process inputs</td>
<td></td>
</tr>
<tr>
<td></td>
<td>? process outputs</td>
<td></td>
</tr>
</tbody>
</table>
Methodology and basic parameters

Method for assessment of environmental impacts throughout the life cycle of a product / technique from raw material acquisition through production, use, end-of-life treatment and disposal

Phases of LCA
Reference: ISO 14040, 14044, 2006
Goal and scope definition

- Environmental impact analysis of coal-based power generation without and with MEA-based CO₂ capture
- No upstream and downstream activities
- Geography: Germany, Europe
- Point in time: 2005 – 2010 – 2020
- Functional unit: 1 kWh_{el}

“Conventional” pulverized coal power plants

1. Coal plant_{2005}: operating in 2005
2. Coal plant_{2010}: installed in 2010
3. Coal plant_{2020}: installed in 2020

Pulverized coal power plants with Amine-based carbon capture

4. MEA_{retrofit1}:
   Coal plant_{2005} + MEA_{2020} retrofitted in 2020
5. MEA_{retrofit2}:
   Coal plant_{2010} + MEA_{2020} retrofitted in 2020
6. MEA_{greenfield}:
   Coal plant_{2020} + MEA_{2020} installed in 2020
Methodology and basic parameters

Power plant and CO₂ capture: Processes and system boundaries

Coal, raw

Coal conditioning

Coal, cond.

Flue gas

NOₓ removal

Flue gas without NOₓ

Dust removal

Flue gas without NOₓ & dust

Desulphurisation

Clean flue gas

Decarbonisation

CO₂

Compression & Liquefaction

Electricity

System boundary

By-products

Solid waste

Emissions into water

Emissions into air

Liquefied CO₂

Raw materials

Operating supplies

Raw materials

Operating supplies

By-products

Solid waste

Emissions into water

Emissions into air

Liquefied CO₂

// Energy Economics Group //
Institute of Energy Research - Systems Analysis and Technology Evaluation (IEF-STE)
### Technical parameters of the power plants

<table>
<thead>
<tr>
<th>Plant parameter</th>
<th>unit</th>
<th>Coal plant2005</th>
<th>Coal plant2010</th>
<th>Coal plant2020</th>
<th>MEAretrofit1</th>
<th>MEAretrofit2</th>
<th>MEA greenfield</th>
</tr>
</thead>
<tbody>
<tr>
<td>combustion capacity</td>
<td>MW&lt;sub&gt;th&lt;/sub&gt;</td>
<td>1164</td>
<td>1200</td>
<td>1424</td>
<td>1164</td>
<td>1200</td>
<td>1424</td>
</tr>
<tr>
<td>gross capacity</td>
<td>MW&lt;sub&gt;el&lt;/sub&gt;</td>
<td>550</td>
<td>600</td>
<td>750</td>
<td>479</td>
<td>527</td>
<td>707</td>
</tr>
<tr>
<td>net capacity</td>
<td>MW&lt;sub&gt;el&lt;/sub&gt;</td>
<td>500.5</td>
<td>552.0</td>
<td>697.0</td>
<td>378.6</td>
<td>426.5</td>
<td>592.0</td>
</tr>
<tr>
<td>gross efficiency</td>
<td>%</td>
<td>47.3</td>
<td>50.0</td>
<td>52.7</td>
<td>41.1</td>
<td>43.9</td>
<td>49.6</td>
</tr>
<tr>
<td>net efficiency</td>
<td>%</td>
<td></td>
<td>43.0</td>
<td>46.0</td>
<td>49.0</td>
<td>32.5</td>
<td>35.5</td>
</tr>
<tr>
<td>electrical equivalence factor</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.2</td>
<td>0.2</td>
<td>0.1</td>
</tr>
</tbody>
</table>

- **Coal plant<sub>2005</sub> – coal plant<sub>2020</sub>**
  - Increase of net capacity
  - Increase of net efficiency: 43% to 49%

- **MEA<sub>retrofit1</sub> - MEA<sub>greenfield</sub>**
  - Increase of net capacity
  - Decrease of energy penalty: 10.5 to 7.4% points
  - Decrease of electrical efficiency factor
**Inventory analysis**

### Inputs

<table>
<thead>
<tr>
<th>Inputs $g/kWh_{el}$</th>
<th>Coal plant_{2005}</th>
<th>Coal plant_{2010}</th>
<th>Coal plant_{2020}</th>
<th>MEA_{retrofit1}</th>
<th>MEA_{retrofit2}</th>
<th>MEA_{greenfield}</th>
</tr>
</thead>
<tbody>
<tr>
<td>hard coal</td>
<td>282</td>
<td>264</td>
<td>247</td>
<td>373</td>
<td>341</td>
<td>291</td>
</tr>
<tr>
<td>cooling water</td>
<td>1398</td>
<td>1222</td>
<td>1077</td>
<td>2126</td>
<td>1834</td>
<td>1389</td>
</tr>
<tr>
<td>ammonia</td>
<td>0.63</td>
<td>0.58</td>
<td>0.54</td>
<td>0.84</td>
<td>0.75</td>
<td>0.64</td>
</tr>
<tr>
<td>lime stone</td>
<td>23</td>
<td>22</td>
<td>20</td>
<td>30</td>
<td>28</td>
<td>24</td>
</tr>
<tr>
<td>MEA</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>2.3</td>
<td>2.1</td>
<td>1.1</td>
</tr>
<tr>
<td>sodium hydroxide</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0.12</td>
<td>0.11</td>
<td>0.09</td>
</tr>
</tbody>
</table>

- **Coal plant_{2005} – coal plant_{2020}**
  - Reduction of hard coal and cooling water
  - Reduction of ammonia and lime stone
  - No MEA solution and sodium hydroxide

- **MEA_{retrofit1} - MEA_{greenfield}**
  - Higher, but decreasing level of hard coal and cooling water
  - Higher, but decreasing level of ammonia and lime stone
  - Decreasing use of MEA solution and sodium hydroxide
  - MEA_{greenfield} most attractive
Inventory analysis

**Output: CO₂**

- **Coal plant\textsubscript{2005} – coal plant\textsubscript{2020}**
  - CO₂ processed = CO₂ emitted
  - Less carbon dioxide processed

- **MEA\textsubscript{retrofit1} - MEA\textsubscript{greenfield}**
  - Higher, but decreasing level of CO₂ processed
  - Fixed share of carbon dioxide captured
  - Lower and decreasing level of CO₂ emitted
  - Decrease of carbon dioxide avoided
  - MEA\textsubscript{greenfield} most attractive
Inventory analysis

Further outputs

<table>
<thead>
<tr>
<th>Outputs $g/kWh_{el}$</th>
<th>Coal plant2005</th>
<th>Coal plant2010</th>
<th>Coal plant2020</th>
<th>MEAretrofit1</th>
<th>MEAretrofit2</th>
<th>MEAgreenfield</th>
</tr>
</thead>
<tbody>
<tr>
<td>waste heat</td>
<td>590</td>
<td>552</td>
<td>518</td>
<td>1179</td>
<td>1076</td>
<td>920</td>
</tr>
<tr>
<td>waste water</td>
<td>120</td>
<td>113</td>
<td>106</td>
<td>159</td>
<td>146</td>
<td>126</td>
</tr>
<tr>
<td>gypsum (FGD)</td>
<td>40</td>
<td>37</td>
<td>35</td>
<td>52</td>
<td>48</td>
<td>42</td>
</tr>
<tr>
<td>waste, sludge, slag</td>
<td>0.90</td>
<td>0.85</td>
<td>0.79</td>
<td>1.26</td>
<td>1.15</td>
<td>1.01</td>
</tr>
<tr>
<td>hazardous waste</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>3.46</td>
<td>3.07</td>
<td>1.22</td>
</tr>
</tbody>
</table>

- Coal plant$_{2005}$ – coal plant$_{2020}$
  - Decrease of waste heat and waste water
  - Decrease of gypsum
  - Decrease of waste, sludge and slag

- $\text{MEA}_{\text{retrofit}}$ - $\text{MEA}_{\text{greenfield}}$
  - Higher, but decreasing level of waste heat and waste water
  - Higher, but decreasing level of gypsum, waste, sludge and slag
  - New: hazardous waste (decreasing level)
  - $\text{MEA}_{\text{greenfield}}$ most attractive
For greenhouse gas potential and photochemical oxidation potential clear advantage for MEA-based capture
For acidification potential no clear advantage for MEA-based capture
For human toxicological potential MEA-based capture unfavourable
For eutrophication potential clear disadvantage for MEA-based capture
Summary and outlook

- High, but decreasing level of energy penalty
- Higher level of material and energy flows and additional flows
- Less CO$_2$ emissions and global warming potential
- Higher level of other emissions and additional emissions
- Subsequently higher level for some environmental impacts

- MEA-based technology superior with respect to CO$_2$
- MEA$_{\text{greenfield}}$ most favorite capture technology
- No clear advantage for MEA-based capture taking into account other environmental impacts
Summary and outlook

Future activities for plant-related analysis:
- Inclusion of CO$_2$ transport and storage and up- and downstream processes
- Analysis of other capture routes and technologies (pre combustion and oxyfuel)

Future activities for full capacity-related analysis:
- Adaptation of plant-related results for dynamic analysis taking into account capacity development
Thank you for your attention
Solid Oxide Electrolysis for Fuel Production

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Solid Oxide Electrolysis for Fuel Production

1. Principle for Solid Oxide Electrolysis Cells (SOECs)
   - Production of hydrogen and synthetic fuel
   - Advantages of SOEC compared to PEM/Alkaline electrolysis

2. Perspectives for SOECs
   - Economy estimation for hydrogen production
   - Synthetic fuel

3. Conclusions and what about the future?
Principle for SOECs

Solid Oxide Fuel Cells

Oxygen electrode
\[ \text{O}_2 + 4e^- \rightarrow 2\text{O}^{2-} \]

Hydrogen electrode
\[ 2\text{H}_2 + 2\text{O}^{2-} \rightarrow 2\text{H}_2\text{O} + 4e^- \]
Solid Oxide Electrolysis Cells

- Consuming water and electricity
- Producing hydrogen
- Electrolysis of $\text{CO}_2 + \text{H}_2\text{O}$ to synthesis-gas ($\text{CO} + \text{H}_2$)

Solid Oxide Fuel Cells

- Consuming hydrogen
- Producing electricity

\[ 2\text{H}_2\text{O} \xrightarrow{\text{÷ 4 e}^-} 2\text{H}_2 + 2\text{O}_2^- + 4\text{e}^- \]

\[ 2\text{O}_2 \xrightarrow{\text{÷ 4 e}^-} 2\text{H}_2\text{O} + 4\text{e}^- + 4\text{H}^+ \]
Principle for SOECs

Solid Oxide Electrolysis Cells

Consuming water and electricity
Producing hydrogen
Electrolysis of $\text{CO}_2 + \text{H}_2\text{O}$ to synthesis-gas ($\text{CO} + \text{H}_2$)

$4 \text{e}^- + \text{O}_2 \rightarrow 2\text{O}^{2-}$

$2\text{H}_2\text{O} \rightarrow 2\text{H}_2 + 4 \text{e}^-$

$2\text{H}_2 + 2\text{O}^{2-} \rightarrow 2\text{H}_2\text{O}$

Morgenkaffen kogt på strøm fra vindmøller

Halvdelen af landets husholdninger har i dag kunnet lave morgenkaffe med støm. Efterårets første alvorlige blæsevejr er nemlig gud for den alternative energiproduktion.

Kl. 9 i dag kunne stømmen fra møllerne dække cirka halvdelen af det samlede årsplan leverer møller ellers kun støm til 20 procent af forbruget.

Med en vindhastighed op omkring 20 m/s i det vestlige Jylland, hvor mange af vindmøllerne placeret, er elproduktionen fra vindmøllerne tæt på det maksimale mulige.

Kommer vindhastigheden op omkring 25 m/s, stopper vindmøllerne derimod.

Gratis el i nat

I nat betød elproduktion fra vindmøllerne, at ubuddet af el på den nordiske grænse var så stort, at elspotprisen i både Øst- og Vestjylland var nul i timerne med høj vind.

Vindmøllerne producerede strøm not til at dække 80 procent af det samlede behov.

Landets kraftværker måtte endda skrue ned for produktionen, fordi der ikke var plads til eksport på de elektriske forbindelser til udlandet.
Principle for SOECs

Solid Oxide Electrolysis Cells

Consuming water and electricity
Producing hydrogen
Electrolysis of CO₂ + H₂O to synthesis-gas (CO + H₂)
## Advantages of SOECs

<table>
<thead>
<tr>
<th></th>
<th>SOEC</th>
<th>Alkaline</th>
<th>PEM</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Reactants and products</strong></td>
<td>$\text{H}_2\text{O} \rightarrow \text{H}_2$</td>
<td>$\text{H}_2\text{O} \rightarrow \text{H}_2$</td>
<td>$\text{H}_2\text{O} \rightarrow \text{H}_2$</td>
</tr>
<tr>
<td></td>
<td>$\text{CO}_2 \rightarrow \text{CO}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Electrolyte</strong></td>
<td>Ceramic</td>
<td>KOH or NaOH</td>
<td>Polymer</td>
</tr>
<tr>
<td><strong>Electrodes</strong></td>
<td>Nickel, ceramics</td>
<td>Nickel</td>
<td>Platinum</td>
</tr>
<tr>
<td><strong>Temperature</strong></td>
<td>850 °C</td>
<td>80 °C</td>
<td>80 °C</td>
</tr>
</tbody>
</table>
Advantages of SOECs

Thermodynamics for water electrolysis

Total energy demand ($\Delta H_f$)

Electric demand ($\Delta G_f$)

Heat demand ($T\Delta S_f$)

Energy demand (KJ/mol)

Temperature (°C)

$1.29 \text{ V}$
Thermodynamics is optimal case ... Real life?

**Solid Oxide Electrolysis Cells**

\[ \text{O}_2 \rightarrow 2\text{O}^{2-} \leftrightarrow 4e^- \rightarrow 2\text{H}_2 + 2\text{H}_2\text{O} \]

**Solid Oxide Fuel Cells**

\[ \text{O}_2 \rightarrow 2\text{O}^{2-} \rightarrow 4e^- \rightarrow 2\text{H}_2 + 2\text{H}_2\text{O} \]
Thermodynamics is optimal case … Real life?

**Solid Oxide Electrolysis Cells**

World record
-3.6 A/cm² at 1.48 V

950 °C, 70% H₂O / 30% H₂

**Solid Oxide Fuel Cells**

850 °C, 50% H₂O / 50% H₂

Cell voltage (V)

-4 -3 -2 -1 0 1 2

Fuel Cell mode

Electrolysis mode

i (A/cm²)

0 1 2
Thermodynamics is optimal case ... Real life?

**Solid Oxide Electrolysis Cells**

\[ \text{Solid Oxide Electrolysis Cells} \]

\[ 0.78 \quad 0.80 \quad 0.82 \]

**Solid Oxide Fuel Cells**

\[ \text{Solid Oxide Fuel Cells} \]

\[ 0.78 \quad 0.82 \]

Cell voltage (V)

Time (h)
SOEC Durability

SEM micrograph of hydrogen electrode after electrolysis

Post examination after electrolysis at 850°C, 70% H₂O, -1 A/cm² for 353 h and -0.5 A/cm² for 227 h
## SOEC Durability

<table>
<thead>
<tr>
<th>Electrolysis cell</th>
<th>Fuel cell [1]</th>
</tr>
</thead>
<tbody>
<tr>
<td>-0.5 A/cm² at 850°C</td>
<td>1.0 A/cm² at 850°C</td>
</tr>
<tr>
<td>~2%/1000 h (1316 h test)</td>
<td>Below 1%/1000 h (1500 h test)</td>
</tr>
<tr>
<td>-1.0 A/cm² at 950°C</td>
<td>1.0 A/cm² at 950°C</td>
</tr>
<tr>
<td>~30%/1000 h (620 h test)</td>
<td>Below 1%/1000 h (1500 h)</td>
</tr>
</tbody>
</table>

Economy estimation for hydrogen production

Cell voltage (V)

850 °C, 50% H₂O / 50% H₂

1.29 V
**Economy estimation for hydrogen production**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Cell voltage</strong></td>
<td>1.29 V (thermo neutral potential)</td>
</tr>
<tr>
<td><strong>Electricity price</strong></td>
<td>1.3 US¢/kWh</td>
</tr>
<tr>
<td><strong>Heat price</strong></td>
<td>0.3 US¢/kWh</td>
</tr>
<tr>
<td><strong>Investment</strong></td>
<td>4000 US$/m² cell area</td>
</tr>
<tr>
<td>Demineralised Water</td>
<td>2.3 US$/m³</td>
</tr>
<tr>
<td><strong>Cell temperature</strong></td>
<td>850 °C</td>
</tr>
<tr>
<td><strong>Heat reservoir temperature</strong></td>
<td>110 °C</td>
</tr>
<tr>
<td><strong>Pressure</strong></td>
<td>1 atm</td>
</tr>
<tr>
<td><strong>Life time</strong></td>
<td>10 years</td>
</tr>
<tr>
<td>Operating activity</td>
<td>50%</td>
</tr>
<tr>
<td><strong>Interest rate</strong></td>
<td>5%</td>
</tr>
<tr>
<td>Energy loss in heat exchanger</td>
<td>5%</td>
</tr>
<tr>
<td>H₂O inlet concentration</td>
<td>95% (5% H₂)</td>
</tr>
<tr>
<td>H₂O outlet concentration</td>
<td>5% (95% H₂)</td>
</tr>
</tbody>
</table>
Economy estimation for hydrogen production
Economy estimation for hydrogen production

Crude oil price today: 66 $/barrel

- 64% Electricity
- 29% Loan
- 3% Heat
- 1% H.E. loss
- 3% Water

Electricity price (US¢/kWh): 1.0, 1.5, 2.0, 2.5, 3.0, 3.5

Equivalent crude oil cost ($/barrel): 25, 30, 35, 40, 45, 50, 55, 60, 65, 70, 75, 80
Economy estimation for hydrogen production

Lifetime (Years)

Equivalent crude oil cost ($/barrel)

Economy estimation for hydrogen production

Crude oil price today
66 $/barrel

3% Heat
1% H. E. loss
3% Water

54% Electricity
39% Loan

6000 $/m²
4000 $/m²
2000 $/m²
Conclusion (hydrogen production)

• Excellent initial electrolysis performance

• Main passivation problem on hydrogen electrode
  — Significant amount of silica impurities

• Long-term durability needs to be improved

• Low hydrogen production price by electrolysis
Production of synthetic fuel

Electrolysis at 850°C

Oxygen electrode
\[ \text{O}_2^\text{-} \rightarrow \text{O}_2 + 4\text{e}^- \]

"Hydrogen" electrode
\[ \text{CO}_2 + 4\text{e}^- \rightarrow 2\text{CO} + 2\text{O}_2^- \]

Cell voltage (V)

\[ i \text{ (A/cm}^2\text{)} \]

50% H$_2$O / 50% H$_2$

50% CO$_2$ / 50% CO
Production of synthetic fuel

Oxygen electrode

$2O^{2-} \rightarrow O_2 + 4e^-$

"Hydrogen" electrode

$2CO_2 + 4e^- \rightarrow 2CO + 2O^{2-}$

Catalyst

$H_2 \rightarrow CH_3OH \rightarrow CH_4$
Production of synthetic fuel

Oxygen electrode

\[ 2O^{2-} \rightarrow O_2 + 4e^- \]

"Hydrogen" electrode

\[ 2CO_2 + 4e^- \rightarrow 2CO + 2O^{2-} \]
Production of synthetic fuel

Production of fuel:
- Catalysis: CH₄ or CH₃OH
- Electrolysis: CO + H₂

Transport:

Consumption:
Fuel cell

Power

H₂O into the atmosphere

CO₂ into the atmosphere

Electricity from wind or water

H₂O

CO₂
Production of synthetic fuel

**Consumption:**
- **Fuel cell**

**Transport**

**Production of fuel:**
- **Catalysis:** CH₄ or CH₃OH
- **Electrolysis:** CO + H₂

**Power**
- Electricity from wind or water
- Mg(OH)₂ + CO₂ (from air) → MgCO₃ + H₂O
- MgO + H₂O → Mg(OH)₂ + Heat
- MgCO₃ + Heat → MgO + CO₂

**CO₂ into the atmosphere**

**H₂O into the atmosphere**

**MgCO₃ + Heat → MgO + CO₂**

**MgO + H₂O → Mg(OH)₂ + Heat**

**Mg(OH)₂ + CO₂** (from air) → **MgCO₃ + H₂O**
Conclusion & Outlook

• Excellent initial electrolysis performance

• Main passivation problem on hydrogen electrode
  — Significant amount of silica impurities

• Long-term durability needs to be improved

• Low hydrogen production price by electrolysis

• Synthetic fuel for the future
Thank you
Extra slides
Crude oil price

NYMEX Crude Oil Futures
Close (Front Month)

May 1, 2006 - May 21, 2007

$66.27
Danmarks første brintanlæg åbner på mandag

Nakskov får landets første anlæg, der ved hjælp af strøm fra vindmøller spalter vand til brint og lít. Samtidig er Lolland vært for en international energikonference.

Af Thomas Lemke | onsdag 16.05.2007 kl. 11:43

På mandag, den 21. maj, klipper den røde snor, og Danmarks første fuldskala brintanlæg begynder at producere brint.

Anlægget, der står i Nakskov, skal omdanne strøm fra vindmøller til brint og dermed være med til at løse problemet med at læge energi fra vindmøller. I første omgang fungerer det som demonstrationsanlæg, men om et par år er der meningen, at det skal indgå i et større anlæg og forringe Vestenskov på Vestlolland med brint.

Når det blæser kraftigt, producerer vindmøllene på Lolland mere strøm, end markedet kan aftage, og prisen dykker til næsten ingenting. Derfor er der store fordele i at anvende overskudstrømmen til at fremstille brint, argumenterer initiativtagerne, selv om meget af energien fra vindmøllestrømmen går tabt under processen.

Brinten kan nemlig lagres i tanke og senere bruges i elværker, som brændstof i brintbiler eller sendes direkte ud til forbrugere via rølefledninger.

Brinten produceres ved hjælp af elektrolyse, hvor ammoniakeltilig vand spaltet til brint og lít ved hjælp af strøm. Ved at bruge overskudstrøm fra vindmøller bliver brinten således CO2-neutral energi, og samtidig er det en brugbar måde at lægge strøm fra vindmøller på.

Åbningen af brintanlægget i Nakskov kl. 17.15 på Nakskov Genbrugsstation, Miljøvej 14, Nakskov. Arrangementet er åbent for alle interesserede.
Morgenkaffe kogt på strøm fra vindmøller

Morgenkaffen kogt på strøm fra vindmøller

27. okt. 2006 10.54 Indland

Halvdelen af landets husholdninger har i dag kunnet lave morgenkaffe med strøm fra en dansk vindmølle. Efterårets første alvorlige blæsevejr er nemlig guf for den alternative energiproduktion.

Kl. 9 i dag kunne stømmen fra møllerne dække cirka halvdelen af det samlede danske elforbrug. På årsplan leverer møller ellers kun støm til 20 procent af forbruget.

Med en vindhastighed op omkring 20 m/s i det vestlige Jylland, hvor mange af Danmarks vindmøller er placeret, er elproduktionen fra vindmøller tæt på det maksimalt mulige.

Kommer vindhastigheden op omkring 25 m/s, stopper vindmøllerne derimod for at beskytte sig selv.

Gratis el i nat

I nat betød elproduktion fra vindmøllerne, at udbuddet af el på den nordiske elbørs, Nord Pool Spot, i går var så stort, at elspotprisen i både Øst- og Vest danmark var nul i timerne mellem kl. 1 og kl. 5 i nat.

Vindmøllerne producerede strøm not til at dække 80 procent af det samlede forbrug klokken 4 i nat.

Landets kraftværker måtte endda skrue ned for produktionen, fordi der ikke var plads til yderligere eksport på de elektriske forbindelser til udlandet.
Use of Alternative Fuels in Solid Oxide Fuel Cells

Anke Hagen

Fuel Cells and Solid State Chemistry Department
Risø National Laboratory
Technical University of Denmark
Outline

• Background
  • Conventional – Alternative fuels
  • Solid Oxide Fuel cells – SOFCs
• SOFC Fuelled with alternative feed stocks
  • Performance/stability
  • Effect of impurities
• Summary - Outlook
Background - Conventional vs. Alternative Fuels

Conventional (based on fossil resources)

Alternative (biomass derived)

Fuels for SOFCs

- Methane
- Syngas
- Hydrogen
- Ethanol

Biomass

Anaerobic digestion

Fermentation

Gasification

Fuels for SOFCs
• Reserves of conventional fuel sources (natural oil and gas) limited
• Economic reasons (increase of crude oil price)
• Dependable supply and availability
• Local, de-central solutions
• Environmental restrictions (CO$_2$ emissions, stringent pollution limits)
Fuel derived from conventional and sustainable sources (e.g., methane, natural gas, hydrogen)

Electrical power and high value heat

- Higher efficiency than conventional power generation systems
- Reduction of emissions and pollution (NOx, CO₂, noise)
- Potential for CO₂ sequestration
- Modular concept (from kW to MW)

Combination of two (potentially) environmentally benign and efficient technologies – fuels derived from biomass and fuel cells to contribute to a sustainable energy supply system
Solid Oxide Fuel Cells – SOFCs - Principle

Anode

Cathode

Electrolyte

Fuel

Air

Electrical Power

H₂

Water

Oxygen ions

Oxygen ions

Oxygen ions

Heat

Water

Electrons

Electrons
Solid Oxide Fuel Cells – SOFCs - Testing

- Test of performance and long-term durability under technologically relevant conditions
- Effect of impurities in the fuel
• CO and H₂ are direct fuels for SOFCs

\[ CO + \frac{1}{2}O_2 \rightleftharpoons CO_2 \] ……
\[ H_2 + \frac{1}{2}O_2 \rightleftharpoons H_2O \]

• Carbon containing fuels are to be converted to CO and H₂, for example by partial oxidation or reforming (see equations):

**Methane**:

\[ CH_4 + H_2O \rightleftharpoons 3H_2 + CO \]

**Ethanol**:

\[ C_2H_5OH + H_2O \rightleftharpoons 4H_2 + 2CO \]

• The SOFC anode acts as catalyst for reforming (see gas analysis):

**Potential for direct feeding of carbon containing fuels in SOFCs**

- **Fuel inlet**
  - methane

- **hydrogen**

- **Fuel outlet**
  - carbon monoxide
SOFC Anode as Catalytic Converter: Methane

\[
\begin{align*}
\text{CH}_4 & \rightarrow \text{CO} + \text{H}_2 \\
\text{CO} + \text{H}_2 & \rightarrow \text{CO}_2 + \text{H}_2\text{O} \\
\text{O}^2- & \text{YSZ electrolyte} \\
\end{align*}
\]
Alternative Fuels - Ammonia

- Becomes liquid at 8 bar: storage and transport
- Comparable power density by weight and volume as carbon fuels such as petrol
- Does not release CO$_2$ under SOFC-process

- Second largest synthetic product in the world (fertilizer, chemicals)
- More than 90% of the overall consumption manufactured by Haber-Bosch-Synthesis ($\text{H}_2+\text{N}_2$ on iron-containing catalyst at elevated temperatures (350 – 550 °C) and pressures above 100 bar)
SOFC Anode as Catalytic Converter: Ammonia

Ammonia

O\textsuperscript{2-} YSZ electrolyte

NH\textsubscript{3} → H\textsubscript{2} + N\textsubscript{2}

YSZ network

H\textsubscript{2} + H\textsubscript{2}O → 2H\textsubscript{2}O

Nickel network

N\textsubscript{2} → 2NH\textsubscript{3}
Long-term performance of SOFCs

5 x 5 cm² SOFC at 850 °C, 1 A/cm² current density, ~75-80% fuel utilization

- Technologically relevant conditions
- Large power output
- Stable performance over 1500 hours (and beyond)

Methane reforming gas mixture: steam to carbon ratio of 2
Gasification gas mixture: wood derived
Ethanol reforming mixture: ethanol/water ratio of 1/1.5

Ethanol reforming gas mixture
Gasification gas mixture
Methane reforming gas mixture
Ammonia: 100%
Biogas – Composition – Minor constituents - Impurities

Saturated with water

Landfill gas, De Mes et al. 2003
Effect of H$_2$S impurities on performance of SOFC

- H$_2$S has two effects:
  - drop of power output
  - increase of degradation rate
  - both effects are reversible until 100 ppm in H$_2$

Power output under a long-term test using hydrogen as fuel on a 5 x 5 cm$^2$ SOFC at 850 °C, 1 A/cm$^2$ current density, hydrogen
Summary - Outlook

• SOFCs were operated:
  • On a number of fuels based on fossil or bio-derived sources
  • With high and stable power-output over 1500 hours and under technologically relevant conditions

• SOFC anodes are versatile catalysts:
  • For steam reforming of carbon containing fuels into CO and H₂
  • Ammonia is decomposed into H₂ and N₂
  • CO and hydrogen are electrochemically converted to CO₂ and H₂O under release of electricity (and heat)

• Hydrogen sulfide in hydrogen fuel has an effect on the performance and stability of SOFCs, which is reversible until 100 ppm

• Effect of characteristic impurities has to be further studied (max. possible concentrations, removal technologies)
We gratefully acknowledge support from our sponsors:

- Topsoe Fuel Cell A/S
- Danish Energy Authority
- Energinet.dk
- EU
- Danish Programme Committee for Energy and Environment
- Danish Programme Committee for Nano Science and Technology, Biotechnology and IT
Test Set-up

- Anode supported cell
- Cathode gas distributor
- Anode gas distributor
- Cell house, alumina
- H₂ flow
- Air flow
- Glass seal
Carbon formation at SOFC anode

- (Thermodynamic) risk of carbon formation for all carbon containing fuels

\[
2CO \rightleftharpoons CO_2 + C \\
CH_4 \rightleftharpoons 2H_2 + C
\]

- Solution: Addition of sufficient water/steam
Thermodynamics of ammonia decomposition

- Nearly complete ammonia decomposition at SOFC operating temperature

![Graph showing ammonia decomposition](image)
Ammonia decomposition

NH₃ → H₂ + N₂
Ammonia – Power output

- **750 °C**
  - Cell voltage in mV
  - Power density in W/cm²
  - Hydrogen/nitrogen 3/1
  - Ammonia

- **850 °C**
  - Cell voltage in mV
  - Power density in W/cm²
  - Hydrogen/nitrogen 3/1
  - Ammonia
Fuel Cell - Shaft Power Packs
FC-SPP
RISØ Energy Conference 2007

Centre Manager
Renewable Energy & Transport
Current Concept

Fuel → Tank → ICE Two Stroke → Application
New Concept

Fuel Cell Shaft Power Pack, FC-SPP

- BoP Controller
- Storage
- Fuel Cell
- Electrical Motor
- Power Electronics

Hydrogen

Fuelling Station

Hydrogen Carrier

User - Interface

Application
Vision:

• Through applied research, development and demonstration, the consortium will create the foundation for a production of hydrogen power packs

• The consortium will look at the market for hydrogen based power packs and develop tools that ensures the basis of a commercial production
Project Team & Budget

Total budget approx. 30 mill. DKK (5.5 mill. USD)
Project duration: 3 years

**Demonstration team**
- Cykellet/DSR Scandinavia
- GMR Maskiner
- Trans-Lift
- Falsled Højtryk

**Research team**
- Aalborg University
- The Danish Technological Institute
- Copenhagen Business School
- Hydrogen Innovation Research Centre

**Development team**
- Dantherm Airhandling
- Migatronic
- H2Logic
- Parker Hannifin DK
- kk-electronic
- Xperion
- EGJ Development
Project Structure

Mercantile Research
CBS

Technical Research
AAU

5 Ph.D. Projects

Applied Research & Development
DTI/HIRC

Fuel Cell Shaft Power Packs

Demonstration projects
4 applications
Component and System Suppliers and End-users
The Research Team

AAU
- T1, Fuel Cells
- T2, Power Electronics
- T3, Balance of Plant

CBS
- M1, Market structure
- M2, Business structure
Technical PhD 1:
Experimental Characterization of Fuel Cells

- Investigation of the cathode manifold flow
- Gas-phase micro-PIV (Particle Image Velocimetry) on bipolar plate channels (at University of Victoria BC, Canada)
- Electrochemical Impedance Spectroscopy (EIS)
- *In situ* temperature measurements (SEMSO)

Nyquist plot

Nyquist plot of air stoichiometry
Technical PhD 2: Power Electronics

- Field measurement of drive profile (DTI)
- Design of propulsion system
- Energy management strategies
- Transient modeling of fuel cell, battery, ultra capacitor, DC/DC converters, DC/AC converters and motor

Electrofuel cell model obtained from Electrochemical Impedance Spectroscopy (EIS)

Source: www.gmr.dk
Technical PhD 3: High Temperature PEM Fuel Cell System Design and Control

- HTPEM fuel cell system design
  - System configuration, evaluation of different system concepts
  - Modeling of system components and fuel cell stack

- Fuel cell system control
  - Identification of critical control states
  - Model based control design
  - Implementation and testing of developed control strategies

- Application control of electrical hybrid vehicle
  - Overall application control strategy control development
  - Performance and field testing of vehicle for model verification
Mercantile PhD 1: FC market drivers and dynamics

FC is a *systemic* innovation: value creation of components depends upon incorporation into a system

- Co-evolution of components, systems, and markets
- Dynamic processes unfolding from *feedback mechanisms*
- Feedbacks transcend disciplinary boundaries (social/technical/economic factors)
- Analytical tool: system simulation
Absorptive capacity – a concept explaining how companies acquire, assimilate and exploit knowledge from external sources

To what extent is research collaboration a vehicle for development of absorptive capacity?

How to manage the collaboration to maximise benefits for participants not only in terms of technological research results, but also development of organisational skills?

Project as an integral part of FC-SPP: using observations and experience of the companies participating in FC-SPP for advancing the research on one hand, and disseminating results to the companies in order to help them better benefit from the cooperation.
Four demonstration projects

1. Cykellet/DSR Scandinavia (Electric powered bike)
2. Trans-Lift (Pallet truck)
3. GMR Maskiner (Truck for maintenance of "green areas")
4. H2O Skypump (Professional high pressure cleaner)
Project types

- Spin-off
- Project
- Open project
  (FC-SPP)
- Closed project
  (Traditional R&D)
- Project duration

Starting point

Goal

100 Years of Innovation
Trans-Lift - case

Trans-Lift design and produce battery powered vehicles for goods handling.

Problems:
- batteries are expensive
- must be replaced from time to time
- must be recharged

Advantages with FC:
- Lower operating costs
- No wasted time for battery charging
Migatronic - case

Migatronic a welding machine producer

Problems:
- None…

Possibilities with FC:
- Create a new product range
- Enter new markets
- More turnover
- Less vulnerable
Thank you!
Overview of U.S. DOE’s Coal RD&D Programs

Clean and Secure Energy From Coal

Scott M. Smouse
International Coordination Team Leader
National Energy Technology Laboratory

Risø International Energy Conference 2007
Copenhagen, Denmark
22-24 May 2007

Office of Fossil Energy
U.S. Department of Energy
Energy Demand Today

101 QBtu / Year
85% Fossil Energy
Coal 23%
Gas 22%
Nuclear 8%
Renewables 6%
Oil 41%

465 QBtu / Year
86% Fossil Energy
Coal 25%
Gas 24%
Nuclear 6%
Renewables 8%
Oil 37%

Energy Demand 2030

131 QBtu / Year
86% Fossil Energy
Coal 26%
Gas 20%
Nuclear 7%
Renewables 7%
Oil 40%

722 QBtu / Year
87% Fossil Energy
Coal 27%
Gas 26%
Nuclear 5%
Renewables 9%
Oil 33%

Energy Demand 2030

World today and tomorrow data from EIA AEO 2007, early release for years 2006 and 2030. World today and tomorrow data from EIA IEO 2006 for years 2006 (extrapolated) and 2030.
Coal dominates electricity generation

U.S. Coal Utilization Outlook

Coal
Natural gas
Nuclear
Renewables
Oil

Upper figure: DOE EIA, AEO 2006, Figure 5
Lower figure: Energy & Electricity per DOE EIA, AER 2004
GDP per U.S. DOC, Bureau of Economic Analysis
250-Year Supply of Coal at Current Demand Levels

U.S. Fossil Fuel Reserves / Production Ratio

- Coal
- Oil
- Natural Gas

EIA, Advance Summary U.S. Crude Oil, Natural Gas, and Natural Gas Liquids Reserves, 2003 Annual Report, September 22, 2004 - for oil and gas reserves data
174 Added GW - Double the 87 GW in DOE’s EIA Annual Energy Outlook 2005

1973 additions greater than total for last 16 years

Coal Adds 154 GW New Capacity Plus 19 GW of CTL (Reference case with 5 additional years to 2030)
DOE Strategic Plan

1.1 **Energy Diversity** – Increase our energy options and reduce dependence on oil, thereby reducing vulnerability to disruption and increasing the flexibility of the market to meet U.S. needs.

1.2 **Environmental Impacts of Energy** – Improve the quality of the environment by reducing greenhouse gas emissions and environmental impacts to land, water, and air from energy production and use.

1.3 **Energy Infrastructure** – Create a more flexible, more reliable, and higher capacity U.S. energy infrastructure.

1.4 **Energy Productivity** – Cost-effectively improve the energy efficiency of the U.S. economy.
R&D Challenges for Coal Technology

- “Near-zero” emissions
- CO$_2$ management
- High efficiency
- Water use
- By-product utilization
- Flexible (feedstocks, products, siting)
- Cost competitive with other energy choices
Office of Fossil Energy’s Coal & Power Program

Support
Presidential Initiatives:
Clear Skies
Climate Change
Energy Security

DEMONSTRATION PROGRAM
Clean Coal
Power Initiative

FUTUREGEN
Integrated sequestration, hydrogen, and power research facility

CORE R&D PROGRAM
Pathway to Clean and Secure Electricity from Coal

Existing Plants

Clean Coal Successes

Near-Zero Emissions

Technology Research, Development & Demonstration
DOE’s Office of Fossil Energy
Advanced Coal Power Systems Goals

• 2010:
  – 45-50% Efficiency (HHV)
  – 99% SO₂ removal
  – NOₓ < 0.01 lb/MM Btu
  – 90% Hg removal
  – $1,000/kW (2002 $)

• 2012:
  – 90% CO₂ capture
  – <10% increase in COE with carbon sequestration

• 2015
  – Multi-product capability (e.g., power, liquid fuels, hydrogen, SNG)
  – 50-60% efficiency (without carbon capture)
Coal & Power Core R&D Program

- Innovations for Existing Plants
- Advanced Integrated Gasification Combined Cycle
- Hydrogen & Syngas
- Carbon Sequestration
- Fuel Cells
- Advanced Research
- Advanced Turbines

Roadmap Developed for Each Program with Industry
Coal & Power Program
Addresses Both Near-Term and Long-Range Needs

- **Short-term**: keep existing fleet in service; prepare for transition to near-zero-emission future
  - $\text{SO}_2$, $\text{NO}_x$, Hg
  - Plant optimization and control
  - Reduced carbon intensity
- **Long-term**: add near-zero emission energy plants
  - IGCCs to market
  - Advanced materials
  - Ultra-high-efficiency hybrid systems
  - $\text{CO}_2$ capture and storage
Carbon Capture and Storage Opportunities
Thousands of Years of Potential Storage Capacity Worldwide

Storage Option

- Deep Saline Formations
- Depleted Oil & Gas Fields
- Coal Seams

Global Capacity (Gigaton CO₂)

Maximum Capacity Potential

Annual World Emissions

24 Gigatons CO₂

## Carbon Sequestration Program

### Technology R&D Pathways

<table>
<thead>
<tr>
<th>CO₂ Capture</th>
<th>Monitoring, Mitigation &amp; Verification</th>
<th>Non-CO₂ GHG Mitigation</th>
<th>Breakthrough Concepts</th>
<th>Non-CO₂ GHG</th>
</tr>
</thead>
<tbody>
<tr>
<td>Post-combustion Capture</td>
<td>Depleting oil reservoirs</td>
<td>Advanced soil carbon measurement</td>
<td>Advanced Capture</td>
<td>Landfill Methane Capture and Use</td>
</tr>
<tr>
<td>Oxygen combustion</td>
<td>Unmineable coal seams</td>
<td>Subsurface measurements</td>
<td>Bio-accelerated sequestration</td>
<td>Mine Ventilation Methane Capture</td>
</tr>
<tr>
<td>Pre-combustion capture</td>
<td>Saline formations</td>
<td>Remote sensing/above-ground MM&amp;V</td>
<td>Niches</td>
<td></td>
</tr>
<tr>
<td>Chemical looping</td>
<td>Enhanced terrestrial uptake</td>
<td>Fate and transport models</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
DOE’s FY2006 Sequestration Program

- Strong industry support
  ~ 39% cost share on projects

- Federal Investment to Date
  ~ $260 Million

- Diverse research portfolio
  ~ 70 R&D Projects

FY2006 Budget

- Sequestration 12%
- Regional Partnerships 27%
- CO2 Capture 19%
- MMV 11%
- Cross-cutting 10%
- Breakthrough Concepts 5%
- Non-CO2 GHG Mitigation 1%
- Congressionally Directed Projects 15%

FY07 Pres. Req. $73.971 Million

[Graph showing DOE Budget (Million $) from 1997 to 2007.
Bar graph showing Federal Investment to Date ~ $260 Million.
Pie chart showing Diverse research portfolio ~ 70 R&D Projects.]

[Image: NETL logo]
Sequestration Program Goals
Develop Technology Options for GHG Management

- **CCS R&D Goals**
  - Options for IGCC and PC-based electricity generating technologies

- **Sequestration/Storage R&D Goals**
  - Predict CO₂ storage capacity with +/- 30% accuracy
  - Develop best practice reservoir management strategies that maximize CO₂ trapping

- **Monitoring, Mitigation & Verification**
  - Ability to verify 95% of stored CO₂
  - CO₂ material balance to >99%

<table>
<thead>
<tr>
<th>Year</th>
<th>COE Penalty IGCC Plants (% Increase)</th>
<th>COE Penalty PC Plants (% Increase)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2002</td>
<td>30</td>
<td>80</td>
</tr>
<tr>
<td>2012</td>
<td>10</td>
<td>20</td>
</tr>
<tr>
<td>2015</td>
<td>&lt;10</td>
<td>10</td>
</tr>
<tr>
<td>2018*</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

*Cost/Energy offset from sequestering CO₂ with criteria pollutants NOX, SOx, H₂S (gasification)
Carbon Storage – Science is Growing

*Understanding of storage mechanisms is critical to viability as a long-term option*

- Physical Trapping
- Residual Phase Trapping
- Solution/Mineral Trapping
- Gas Adsorption

Sources: Friedmann, LLNL 2006
Carbon Sequestration Regional Partnerships
“Developing the Infrastructure for Wide-Scale Deployment”

Phase I (Characterization)
- 7 Partnerships (40 states)
- 24 months (2003-2005)

Phase II (Field Validation)
- 4 years (2005 - 2009)
- All seven Phase I partnerships continued
- $100 million federal funds
- $45-million cost share

Phase III (Deployment)
- 10 years (2008-2017)
- Several large-scale injection tests
Regional Carbon Sequestration Partnerships
Phase II Validation Tests - Injecting between 750 – 525,000 tons of CO₂

Representing:
- >300 Organizations
- 40 States
- 4 Canadian Provinces
- 3 Indian Nations
- 34% cost share

Field Test Type
- Oil bearing (9)
- Gas bearing (1)
- Saline aquifer (10)
- Coal seam (5)
- Terrestrial (11)
Break-Through Capture Concepts

**Ionic Liquids**
- CO$_2$ is *highly soluble* in some ionic liquids
- Non-volatile liquid and high thermal stability
- Ability to capture SO$_2$ with one solvent

**Metal Organic Frameworks**
- Highly porous materials
- Thermally stable
- High loading capacities
- Low manufacturing costs
Break-Through Capture Concepts

Thermally Optimized Membranes

- Order of magnitude higher selectivity than current polymers
- Selective from room temp to 400°C
- Promising preliminary results

Ceramic Autothermal Recovery (CAR) Technology

- Oxy-fuel combustion option for power generation
- High-temperature, steady-state process
- Perovskites pellets, fixed bed
- Oxygen-enriched product stream, high O₂ recovery
Ongoing, Large-Scale CO₂ Sequestration Projects

**Weyburn CO₂ EOR Project**
- Pan Canadian Resources
- 200-mile CO₂ pipeline from Dakota Gasification Plant
- Enhanced Oil Recovery in Canada

**Sleipner North Sea Project**
- Statoil
- CO₂ sequestered - Utsira Formation
- Currently monitoring CO₂ migration
- Separates CO₂ from natural gas
- $36-50/tonne CO₂ tax
DOE’s Coal Demonstration Programs
Implemented Through Competition

- Clean Coal Technology Program - 1985-1993
- Power Plant Improvement Initiative - 2001
- Clean Coal Power Initiative - 2002-2012

Industry / Government Partnership

Minimum 50% Non-Federal Cost Share

Existing Power Plant Fleet

Fleet of Tomorrow

Repayment
IGCC Technology in Early Commercialization
*U.S. Coal-Fueled Plants*

- **Wabash River**
  - 1996 Powerplant of Year Award*
  - Achieved 95% availability

- **Tampa Electric**
  - 1997 Powerplant of Year Award*
  - First dispatch power generator

*Nation’s first commercial-scale IGCC plants, each achieving > 95% sulfur removal > 90% NOx reduction*
Clean Coal Power Initiative

- 10-year program
- 4 rounds of solicitations
- Drivers
  - Overall
    - Clear Skies Initiative
    - Reduced carbon intensity
    - Zero emissions technology target
    - Energy/economic security
  - Round 1 (Broad)
    - Advanced coal-based power generation
    - Efficiency, environmental & economic improvements
  - Round 2 (Prioritized)
    - Gasification
    - Hg control
FutureGen: A Global Partnership Effort

One-billion dollar, 10-year project to create world’s first coal-based, zero-emission electricity and hydrogen plant

President Bush, 27 February 2003

- Research platform to accelerate deployment of promising technologies
- Broad participation from mining and electricity sectors
- 12 member industry-led consortium with international collaboration
FutureGen Concept

Hydrogen Pipeline

Electricity

Refinery

Geological Sequestration

CO₂
FutureGen: Integrating Function for Fossil Energy R&D Program

Fuel Cells

Gasification with Cleanup Separation

H₂ Production

Optimized Turbines

Carbon Sequestration

System Integration
FutureGen Project
Supporting FutureGen is Major Goal of FE’s R&D Programs

- Industry-led project with government oversight & international participation
  - Signed Cooperative Agreement with DOE on 2 Dec. 2005
  - Project structuring to Jan. 2007
  - Design to July 2009
  - Construction to July 2012
  - Operations to July 2016
  - Site monitoring to July 2018

- International Participation:
  - India and South Korea signed Protocols of Intent to join
  - China and Japan expressed strong interest in joining

- Industry will choose project site & backbone technologies
  - Down selected to 4 potential sites
U.S. Government Commitment to Clean Energy From Coal

FY 2006 Coal Program Funding

<table>
<thead>
<tr>
<th>Program</th>
<th>Thousand $</th>
</tr>
</thead>
<tbody>
<tr>
<td>FutureGen</td>
<td>17,820</td>
</tr>
<tr>
<td>Clean Coal Power Initiative</td>
<td>49,500</td>
</tr>
<tr>
<td>Innovations for Existing Plants</td>
<td>25,146</td>
</tr>
<tr>
<td>Gasification</td>
<td>55,886</td>
</tr>
<tr>
<td>Turbines</td>
<td>17,820</td>
</tr>
<tr>
<td>Sequestration</td>
<td>66,330</td>
</tr>
<tr>
<td>Fuels</td>
<td>28,710</td>
</tr>
<tr>
<td>Fuel Cells</td>
<td>61,380</td>
</tr>
<tr>
<td>Advanced Research</td>
<td>52,622</td>
</tr>
<tr>
<td><strong>TOTAL COAL</strong></td>
<td><strong>375,214</strong></td>
</tr>
</tbody>
</table>

Historic and Continued U.S. Support

- More than $20 billion over past 30 years
- FutureGen: $1 billion through 2018
- Carbon Sequestration: $450 million through 2016
Energy Policy Act of 2005 (EPAct) and Coal

Seven areas directly affect coal-related technologies:

<table>
<thead>
<tr>
<th>Title IV, Subtitle A</th>
<th>Title XIII Subtitle A</th>
<th>Title IX, Subtitle F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clean Coal Power Initiative</td>
<td>Clean Air Coal Program</td>
<td>Fossil Energy Research and Development</td>
</tr>
<tr>
<td>$1.8bn, 2006-2014</td>
<td>Electricity Infrastructure Credit for Investment in Clean Coal Facilities</td>
<td>$1.137bn 2007-2009</td>
</tr>
<tr>
<td>Title IV, Subtitle B</td>
<td>Accelerated amortization for new air pollution control equipment; $ Indeterminate</td>
<td>Title XVII</td>
</tr>
<tr>
<td>Clean Power Projects</td>
<td></td>
<td>Incentives for Innovative Technologies</td>
</tr>
<tr>
<td>Grants, Loans, Loan Guarantees, and Cost Sharing</td>
<td></td>
<td>Loan guarantees for gasification projects</td>
</tr>
<tr>
<td>$ Indeterminate</td>
<td></td>
<td>$ Indeterminate</td>
</tr>
<tr>
<td>Title IV, Subtitle C</td>
<td>Title XIII Subtitle B: Domestic Fossil Fuel Security</td>
<td></td>
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<tr>
<td>Coal and Related Programs</td>
<td>Production tax credits</td>
<td></td>
</tr>
<tr>
<td>Clean Air Coal Program</td>
<td>for unconventional fuels, incl. CTL</td>
<td></td>
</tr>
<tr>
<td>$3.0bn, 2007-2013</td>
<td>$ Indeterminate</td>
<td></td>
</tr>
</tbody>
</table>
Progress Towards Advanced Technology Implementation

- Congressional Tax Credit Authorization of $1.65 Billion
- 22 applications were received
  - representing $27.7 billion in proposed projects
  - requesting $2.3 billion in tax credits
  - 18 IGCC and 4 adv. coal-based generation projects
- First Round Awards of Approximately $1 Billion

**First Round Recipients Include:**

- Duke Energy - Edwardsport IGCC Project, Edwardsport, IN
- E.ON U.S., Louisville Gas and Electric and Kentucky Utilities Co., Bedford, KY
- Tampa Electric Company, Polk County, FL
- Carson Hydrogen Power, LLC - Carson Hydrogen Power Project, Carson, CA
- Southern Company - Mississippi Power Company, Kemper County, MS
- TX Energy, LLC - Longview Gasification and Refueling Project, Longview, TX
- Duke Energy - Cliffside Modernization Projects, Cleveland and Rutherford County, NC
Support for technology development is one of Government’s tools to ensure a sustainable, secure, and affordable energy future.
Visit Our Websites

**Fossil Energy website:**
www.fe.doe.gov

**NETL website:**
www.netl.doe.gov
The UK Energy Research Atlas: A Tool for Prioritising and Planning Energy R&D

Risø International Energy Conference 2007
Energy Solutions for Sustainable Development

22-24 May 2007

Jim Skea, Research Director
UK Energy Research Atlas

- Why?
- What?
- Who and how?
- What next?
ENERGY RD&D IN THE IEA

Source: IEA

- United States
- IEA-Europe
- Japan
UK ENERGY R&D SINCE 1992

Source: IEA
ENERGY R&D IN THE UK

- **Over-arching**
  - Energy Research Partnership, little resource. Thinks about the “big picture”

- **University-led**
  - Research Councils Energy Programme (£70m pa), including UK Energy Research Centre (£3m pa)

- **Applied R&D**
  - Department of Trade and Industry Technology Programme
  - Various specific clean energy schemes
  - Energy Technologies Institute, not yet up and running (up to £100m pa, on target for £60m pa)

- **Demonstration/Deployment**
  - Environmental Transformation Fund, not yet up and running, resources unclear
Why?

- Evidence base
- Finding research partners/providers
- Locating your own position
- Links along innovation chain
- UK and EU/international links

The first tool to show the live status of energy R&D in the UK
What?

“an authoritative and comprehensive account of capabilities and unsolved research problems across the energy domain”

Research Landscape
characterising energy-related research activities and capabilities in the UK

Research Register
an online, searchable database of energy-related awards and projects

Research Roadmaps
identifying the sequence of research problems to be overcome before new technologies can be commercially viable
IEA R&D Nomenclature

- Energy demand
- Fossil fuels: oil, gas and coal
- Renewable energy sources
- Nuclear fission and fusion
- Hydrogen and fuel cells
- Other power and storage
- Other cross-cutting technologies and research
Accessing the Landscapes

Structure

- Overview
- Capabilities Assessment
- Basic and Applied Strategic Research
- Applied Research
- Development and Demonstration Funding
- Research Facilities and other Assets
- Networks
- UK Participation in EU Activities
- International Initiatives
### Table 3.2: Key Research Providers

<table>
<thead>
<tr>
<th>Name</th>
<th>Description</th>
<th>Sub-topics covered</th>
<th>No of staff</th>
<th>Field</th>
</tr>
</thead>
<tbody>
<tr>
<td>Forest Research, Forestry Commission, Edinburgh and Alice Holt, Surrey</td>
<td>Research on modelling yield in SRC bioenergy trees, biofuel as a source of renewable energy and GHG balance of bioenergy cropping systems.</td>
<td>• SRC Yield Models in development&lt;br&gt;• Woodfuel as a resource&lt;br&gt;• Member of TSEC-BIOSYS&lt;br&gt;• Climate change programme to predict the effects of future climates on woodfuel resource in the UK. Environmental sustainability.&lt;br&gt;• Policy development and advice to central Government.</td>
<td>4 Principal Investigators</td>
<td>Agriculture</td>
</tr>
<tr>
<td>School of Biological Sciences, University of Aberdeen</td>
<td>School of Biological Sciences is actively engaged in research on the GHG mitigation potential of bioenergy crop systems</td>
<td>• GHG mitigation and carbon balance of bioenergy crop systems&lt;br&gt;• Member of TSEC-BIOSYS&lt;br&gt;• Environmental sustainability.</td>
<td>2 Faculty</td>
<td>Biological Sciences</td>
</tr>
<tr>
<td>Sustainable Environment Research Centre, University of Glamorgan</td>
<td>Two research units - the Wastewater Treatment Research Unit and the Hydrogen Research Unit. The aims are to produce high quality scientific research in the field of sustainable environment in particularly acting as an umbrella body for the Wastewater Treatment Research Unit and the newly approved Hydrogen Research Unit; to advance knowledge and provide trained scientists and engineers to meet the needs of industry; to enhance the standing of the University of Glamorgan both nationally and internationally.</td>
<td>• Expertise in dark fermentation reactions for hydrogen production&lt;br&gt;• Member of TSEC-BIOSYS consortium&lt;br&gt;• Member of SUPERGEN Fuel cells consortium&lt;br&gt;• Member of the SUPERGEN Sustainable hydrogen economy consortium&lt;br&gt;• Expert in biohydrogen production including anaerobic and aerobic digestion.</td>
<td>7 Faculty</td>
<td>Biological Sciences</td>
</tr>
<tr>
<td>Institute of Grassland and Plant Sciences</td>
<td>Focus is on breeding and environmental sustainability.</td>
<td>• Coordinator of DEFRA crop.</td>
<td>3 Principal Researchers</td>
<td>Biological Sciences</td>
</tr>
</tbody>
</table>
Searching the Register

Reference Number: GR/826965/01

Title: UK Sustainable Hydrogen Energy Consortium

Status: Started

Energy Categories:
- HYDROGEN and FUEL CELLS (Hydrogen, Hydrogen production) 10%
- HYDROGEN and FUEL CELLS (Hydrogen, Hydrogen storage) 7%
- HYDROGEN and FUEL CELLS (Hydrogen transport and distribution) 5%
- HYDROGEN and FUEL CELLS (Hydrogen, other infrastructure and systems R&D) 5%
- HYDROGEN and FUEL CELLS (Hydrogen, Hydrogen end uses (incl. combustion; excl. fuel cells)) 10%

Research Types:
- Basic and strategic applied research 100%

Science and Technology Fields:
- PHYSICAL SCIENCES AND MATHEMATICS (Chemistry) 60%
- PHYSICAL SCIENCES AND MATHEMATICS (Metallurgy and Materials) 20%
- SOCIAL SCIENCES 20%

UKERC Cross Cutting Characterisation:
- Not Cross-cutting 90%
- Sociological economical and environmental impact of energy 10%

Principal Investigator:
Dr. T. Mays
T.J.Mays@bath.ac.uk
Chemical Engineering
University of Bath

Award Type: 3
Funding Source: EPSRC
Start Date: 01 April 2003
End Date: 01 March 2007
Duration: 48 months
Total Grant Value: £3,481,041
Industrial Sectors: Environment; Power
Region: South West
Programme: Infrastructure and Environment

Investigators:
Principal Investigator: Dr. T. Mays, Chemical Engineering, University of Bath (99.981%)
Other Investigators:
Dr. P. Dinsdale, Sch of Applied Sciences, University of Glamorgan (0.001%)
Professor P. Edwards, Oxford Chemistry, University of Oxford (0.001%)
Dr. J. Gamson, Sch of Chemistry, University of Birmingham (0.001%)
Professor D. M. Grant, Sch of Mech, Materials, Manuf Eng & Mgt, University of Nottingham
Technology Roadmap Characterisation

Bibliographic
- weblink, geographical focus, abstract

Outputs

Architecture
- timescales, trends and drivers, enablers, performance targets, rd&d mapping, critical assessment of capabilities

Process
- methods, stakeholder engagement, scale, re-visiting

Actions identified
- types, timescales, priorities, dependencies, responsibilities
Who Contributed and How?

UKERC researchers

Rutherford Appleton Labs

Partners:
- UKAEA
- Dalton Institute
- Energy Helpline, UK National Contact Point
- British Coal Utilisation Research Association

Atlas Advisory Group
- UKERC plus Carbon Trust, DTI, Environmental Research Funders Forum, E.ON UK, EPSRC, Office of Science and Innovation
How It’s Been Used

- background information for presentations on the UK energy research
- information on local activities for regional development authorities etc
- evidence supporting criteria for the work programme of the new Energy Technologies Institute
- patterns of research activity for the International Science Panel on Renewable Energy
- identifying partners for establishing consortia for EU Framework Programme bids.
What Next?

The Research Atlas will never be finished....

Immediate Tasks
- Peer review/community feedback
- Fill in missing Landscape/roadmap sectors
- Synthesise existing roadmap information
- Content management system/database development

Longer Term
- 6 monthly review cycle
- Enhance international dimension
- Private sector
- Address sectors not covered so far
- New UK-relevant roadmaps where the need exists
European and global perspectives for CCS

Martine Uyterlinde, Heleen Groenenberg

Models and partners

- MARKAL: ECN, Netherlands
- PRIMES/PROMETHEUS: ICCS/NTUA, Greece
- MESSAGE: IIASA, Austria
- POLES: IPTS, Spain
- GMM: PSI, Switzerland
- PACE: ZEW, Switzerland
- TIMES-EE, NEWAGE-W: IER, Germany
- NEMESIS: ERASME, France
- ETP: IEA, France
- NEMS: DOE/EIA, US
- DNE21+: RITE, Japan
- AIM: NIES, Japan
- MAPLE: Natural Resources Canada
## CASCADE-MINTS

<table>
<thead>
<tr>
<th>Region</th>
<th>Top down</th>
<th>Bottom up</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Macro-economic</td>
<td>Computable General Equilibrium</td>
</tr>
<tr>
<td>Global, US, Canada</td>
<td>AIM*</td>
<td>DNE21+</td>
</tr>
<tr>
<td></td>
<td>NEWAGE-WPACE*</td>
<td>ETP GMM MESSAGE</td>
</tr>
<tr>
<td></td>
<td></td>
<td>PROMETHEUS (stochastic)</td>
</tr>
<tr>
<td>Europe</td>
<td>NEMESIS*</td>
<td>MARKAL Europe TIMES-EE</td>
</tr>
</tbody>
</table>
CO₂ capture and storage

IPCC 2005
CCS in models

- Post combustion (pulverized coal, NGCC)
- Pre combustion (IGCC, biomass gasification)
- No oxyfuel
- Some: H₂, cement, cokes, ammonia
- Wide variety of storage options or
  1 generic technology with infinite capacity
CCS in models (ctd.)

Varying assumptions on:
• Investment costs
• O&M costs
• Energy penalty
• Capture efficiency
• Learning rate

No assumptions on:
• Public acceptance
• Risks and safety regulations
Two policy approaches

- **CCS standards:**
  - CO$_2$ capture obligation all new plants $>$2015
  - not for peaking plants ($<$10 MW or utilisation $<$ 20%)
  - not for small CHP

- **CO$_2$ emission cap:**
  - emission level same as CCS standards
  - emissions trading only
CO₂ emission cap

- Emission level same as CCS standards
- Flexibility in technologies used
- Lower costs
- Lower penetration CCS
- More renewables and nuclear
- Shift to natural gas
CCS standards case

Net CO2 emissions

CO2 emissions captured

Net CO2 emissions baseline

substitution effect

sectoral shift of emissions

GMM

MESSAGE

2000 2010 2020 2030 2040 2050

[0, 70] Gton CO2

2050

Net CO2 emissions

CO2 emissions captured

Net CO2 emissions baseline
CCS standards (ctd.)

• 16-30% of global CO$_2$ captured in 2050 (7-19 GtCO$_2$)
• 21-23% of total CO$_2$ captured in Europe
• Variation due to differences in:
  - projections primary energy mix
  - assumptions technology learning
  - future costs capture and renewables
  - potentials renewables, constraints nuclear
CCS standards (ctd.)

• Large capacities w/o CCS remain in system
• Peak gas capacity and renewables gain most
• Substitution effect: nuclear and renewables more competitive (> energy penalty)
• CCS may lead to leakage of emissions to other sectors (MESSAGE), e.g. biomass in power or more H₂ from fossil fuels
• Coal-based CCS dominates, esp IGCC
• Biomass gasification negative emissions but high capital costs
CO₂ storage capacity

- IPCC 1995: 675-900 GtCO₂ in depleted hydrocarbon fields
CO$_2$ storage capacity (ctd.)

TIMES EE
EU Emissions Trading Scheme

• Cost-effective instrument, however:
• Preference for low-cost abatement options
• Innovation market failure
• Need for complementary policies
Complementary incentives for CCS

- CCS obligation
- Low-carbon portfolio standard + tradable certificates
- Public financial support
  - Investment support
  - Feed-in subsidies
  - CO\(_2\) price guarantee
Any additional instrument will reduce demand for EUAs and lower CO₂ market price unless cap is lowered accordingly.
Interaction
complementary incentives ↔ ETS (ctd)

• MS incentives small scope; less market impact
• *Any* additional instrument will reduce demand for EUAs and lower CO\(_2\) market price *unless* cap is lowered accordingly

→ *Lower cap in MS*
→ *New entrants: no or limited allowances*
Interactions
complementary incentives for CCS

Renewable energy:
- Diversion of resources + attention
  - \( \rightarrow \) \( \textit{\% renewables contingent on CCS implemented} \)

Innovation:
- Cost reduction discouraged
  - \( \rightarrow \textit{Obligation} \)

Electricity market:
- Technical reasons for placing CCS as baseload option,
  however O&M cost lead to higher electricity price

Security of energy supply:
- CCS only contributes if gas prices spur a shift to coal, and
  \( \text{CO}_2 \) prices are high enough for CCS
Conclusions

- Up to 30% of global CO$_2$ captured and stored in 2050
- Up to 22% in Europe (slower growth power sector)
- Penetration renewables and nuclear accelerated if CCS is mandatory
- ETS cost-effective incentive for CO$_2$ reduction, however market failures and low prices may hinder CCS deployment
- Interaction of complementary incentives with ETS requires cap adjustment
Thank you


The CASCADE MINTS project is funded by the EU under the Scientific Support to Policies priority of the Sixth RTD Framework Programme

Martine Uyterlinde: uyterlinde@ecn.nl
Heleen Groenenberg: groenenberg@ecn.nl
Solar Energy
Status and Perspectives

By Peter Ahm, Director, PA Energy A/S

Solar Energy – Status & Perspectives
PA Energy A/S
The Potential for Solar Energy

One hour’s sunshine ~ the global annual energy supply
Solar Energy in the World Energy Supply

2004 Fuel Shares of World Total Primary Energy Supply*

- Gas: 20.9%
- Oil: 34.3%
- Coal: 25.1%
- Nuclear: 6.5%
- Renewables: 13.1%
- Non-renew. Waste: 0.2%
- Combustible Renewables and Ren. Waste: 10.6%
- Hydro: 2.2%
- Other**: 0.5%
- Tide: 0.0004%
- Wind: 0.064%
- Solar: 0.039%
- Geothermal: 0.414%

* TPES is calculated using the IEA conventions (physical energy content methodology). It includes international marine bunkers and excludes electricity/heat trade. The figures include both commercial and non-commercial energy.
** Geothermal, solar, wind, tide/wave/ocean.
Totals in graph might not add up due to rounding.

Source: IEA
## RE Characteristics

<table>
<thead>
<tr>
<th></th>
<th>World electricity production 2003 (TWh)</th>
<th>Electricity generation costs 2003 (€ cents/kWh)</th>
<th>World estimated technical annual generation potential (heat &amp; electricity) ($10^3$ TWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydroelectricity</td>
<td>3 000</td>
<td>2-8</td>
<td>14</td>
</tr>
<tr>
<td>Bio-energy</td>
<td>175</td>
<td>5-6</td>
<td>77 - 124</td>
</tr>
<tr>
<td>Wind energy</td>
<td>75</td>
<td>4-12</td>
<td>178</td>
</tr>
<tr>
<td>Geothermal power</td>
<td>50</td>
<td>2-10</td>
<td>1400</td>
</tr>
<tr>
<td>Marine energy</td>
<td>0.5</td>
<td>[8-15]*</td>
<td>No number available</td>
</tr>
<tr>
<td>Solar thermal energy</td>
<td>0.8</td>
<td>12-18</td>
<td></td>
</tr>
<tr>
<td>PV</td>
<td>2.5</td>
<td>25-65</td>
<td>440</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>3300</strong></td>
<td></td>
<td><strong>&gt;2100</strong></td>
</tr>
</tbody>
</table>

*estimated costs as no commercial plant is yet in production

*Current global energy consumption: 110*
RE Growth Rates

Annual Growth of Renewables Supply from 1971 to 2004

- Geothermal: 7.5%
- Solar: 28.1%
- Wind: 48.1%
- Tide: 0.3%
- TPES: 2.2%
- Renewables: 2.3%
- CRW: 2.1%
- Hydro: 2.6%
- Other: 8.2%
Solar Energy Technologies

- Photovoltaics (PV) - electricity
- Solar Hot Water System (SHW)
- Concentrated Solar Thermal (CST) - electricity
Presentation: Focus on PV

1. Status of technology
   a) Technology development
   b) Market development

2. Drivers & trends in development

3. Challenges, or problems, facing progress
1. Generation PV’s

- Based on mono- og poly-crystalline Si
- In 2006 ~ 90% of the market, poly-X alone > 50 %
- Expected in 2015 to cover > 50 % of the market
- Efficiency: 15-20%
- The PV sector ”work horse”
2. Generation PVs

- Thinfilm types
  - Si, CdT, CIS etc.
- Promising technology
  - Potentially cheap
    - Little materials
    - Mass production
- Problem
  - Manufacturing
  - Stability
- Efficiency: 7-15%
- Time horizon: +2010
3. Generation PVs

- High-efficiency thinfilms
  - stacked types: 30-60 % efficiency
  - PEC types
  - Polymer based types

- Time horizon: more than 15 years for commercial products (PEC on the market)
PV Technology Trends
Trends in market share per main PV technology

[Bar chart showing market share trends for different PV technologies from 1999 to 2003. The chart includes categories such as mono c-Si, poly c-Si, CdTe, a-Si, CIS, ribbon/sheet c-Si.]
Market Development 1

- Annual growth rate since 2000 around 40%
- Market value (global): >15 billion € (as wind energy)
- Cell production in 2006: 2,5 GW
- Expected module production in 2010: ~ 6-8 GW)
Market Development 2
Annual growth rates in %
Trends in Efficiency

Reported max. $\eta$: 37 % (Emcore 2007)
# Job Creation in Energy

<table>
<thead>
<tr>
<th>Sector</th>
<th>Jobs, year /MTOE (fuel production)</th>
<th>Jobs - year / Terawatt-hour (fuel production + power generation)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Petroleum&lt;sup&gt;a&lt;/sup&gt;</td>
<td>395</td>
<td>260</td>
</tr>
<tr>
<td>Offshore oil&lt;sup&gt;a&lt;/sup&gt;</td>
<td>450</td>
<td>265</td>
</tr>
<tr>
<td>Natural gas&lt;sup&gt;a&lt;/sup&gt;</td>
<td>428</td>
<td>250</td>
</tr>
<tr>
<td>Coal&lt;sup&gt;a&lt;/sup&gt;</td>
<td>925</td>
<td>370</td>
</tr>
<tr>
<td>Nuclear&lt;sup&gt;b&lt;/sup&gt;</td>
<td>100</td>
<td>75</td>
</tr>
<tr>
<td>Wood energy&lt;sup&gt;c&lt;/sup&gt;</td>
<td></td>
<td>733 – 1067</td>
</tr>
<tr>
<td>Hydro&lt;sup&gt;d&lt;/sup&gt;</td>
<td></td>
<td>250</td>
</tr>
<tr>
<td>Minihydro&lt;sup&gt;e&lt;/sup&gt;</td>
<td></td>
<td>120</td>
</tr>
<tr>
<td>Wind</td>
<td>918&lt;sup&gt;(e) – 2,400&lt;sup&gt;(f)&lt;/sup&gt;</td>
<td></td>
</tr>
<tr>
<td>Photovoltaics</td>
<td>29,580&lt;sup&gt;(g) – 107,000&lt;sup&gt;(g)&lt;/sup&gt;</td>
<td></td>
</tr>
<tr>
<td>Bioenergy (from sugarcane)&lt;sup&gt;h&lt;/sup&gt;</td>
<td>3,711–5,392</td>
<td></td>
</tr>
</tbody>
</table>

**Sources:**
(a) Grassi [1996]; (b) Electric Power International [1995] *apud* Grassi [1996]<sup>1</sup>; (c) Grassi [1996]<sup>2</sup>; (d) Carvalho and Szewcz [2001]; (e) Perez [2001]; (f) IEA [2002]<sup>b</sup>; (g) REPP [2001]<sup>h</sup>; IEA [2002]<sup>b</sup>; (h) UNICA [2003]<sup>g</sup>.

---

<sup>1</sup> 500 people was the staff level for operation of a 1350 MW nuclear power plant in the U.S., producing 9.45 TWh/yr, or 2,138 Mtoe/yr at efficiency of 38%.  
<sup>2</sup> Electric generation based on herbaceous crops (5.5 direct jobs/MWe) and on forestry crops (8 direct jobs/Mwe), utilization 7,500 h/yr.  
<sup>3</sup> World installed capacity for wind 17,300 MW, utilization 2,000 h/yr and 4.8 jobs/MW.  
<sup>4</sup> Including 12 different activities to construct, transport, install and service 1 MW of PV (not included economies of scale between 2 kW and 1 MW), world installed PV capacity is 800 MW.  
<sup>5</sup> Utilization of 1,200 h/yr, 35.5 jobs/MW (included 15 different activities to manufacture, transport, install and service 1 MW of wind power).  
<sup>6</sup> Ethanol industry provides 33 direct jobs/ million liter in Brazil, where ethanol production in the 1992-2001 period ranged between 10.6-15.4 billion liters/yr (LHV of ethanol 6,500 kcal/kg and density 0.8 kg/l). energy production comprised 7 Mtoe of ethanol fuel, plus 9.6 TWh/yr of cogeneration (installed capacity 2,000 MW, utilization of 4,800 hours/yr).
Trends in PV module prices
PV Learning Curve

Power Modules (1976-2001)

Price of Power Modules (2001 $)

Estimate 1976 - 2001 (m = -0.32; b = 1.61; R² = 0.9880): PR = 80.0%

Estimate 1987 - 2001 (m = -0.37; b = 1.74; R² = 0.9323): PR = 77.0%
Learning Curves – Energy Technologies

- PV is special: technology generations known
When will PV be competitive?

- IEA (Wene 2000) productionen of PV modules shall be increased by a factor 100 before competitiveness with fossil fuels (from 300 MW/y to 30 GW/y)
- With an annual average growth rate of 30% this is achieved in 15 years (2015)
Competitiveness of market sectors

Market Segments

Off-Grid Industrial

Consumer

Off-Grid Residential

On-Grid

Economically viable

Dependant on market support programs

Market in 2005

Source: Strategies Unlimited

96 MW / 8%

24 MW / 2%

108 MW / 9%

970 MW / 81%

Source: Strategies Unlimited

Solar Energy – Status & Perspectives
PA Energy A/S
Competitiveness of PV Solar Electricity

- proven in the three segments:
  - industrial off-grid
  - consumer
  - rural electrification
- coming soon in grid-connected systems
  - First, in local replacement of peak tariff electricity in liberalized southern OECD countries (… 2010 … 2015)
  - Second, the same in more northern OECD countries (… 2020 … 2025)
Competitiveness vs. grid power

Source: EPIA towards an Effective Industrial Policy for PV.ppt/05.06.2004/Rapp @RWE Schott
Technology Evolution

• Is there a necessity for 2nd and 3rd generation technologies to replace c-Si wafer technology for module production cost below 1 €/W?

• **No**, but utilize new features of thin film and new concept cells to serve additional customer needs!
## Technology evolution

1) No 1€/W limit for c-Si modules

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>c-Si ribbon (e.g. EFG)</td>
<td>0,7</td>
<td>0,6</td>
</tr>
<tr>
<td>multicryst./Cz-wafer</td>
<td>0,9 / 1,1</td>
<td>0,8 / 1,0</td>
</tr>
<tr>
<td>thin-film (e.g. a-Si, CIS)</td>
<td>0,7</td>
<td>...</td>
</tr>
</tbody>
</table>
## Technology evolution

**EPIA Roadmap - c-Si technology**

<table>
<thead>
<tr>
<th></th>
<th>2000</th>
<th>2010</th>
<th>2020</th>
</tr>
</thead>
<tbody>
<tr>
<td>feedstock</td>
<td>25</td>
<td>20</td>
<td>15 €/kg</td>
</tr>
<tr>
<td>wafer</td>
<td>300</td>
<td>200</td>
<td>100 µm</td>
</tr>
<tr>
<td>cell</td>
<td>14-17</td>
<td>17-20</td>
<td>19-22 %</td>
</tr>
<tr>
<td>module</td>
<td>long term stable, low cost/m² technology</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

In the long run integrated manufacturing of thin wafers (100 µm or less) and subsequent cell and laminate making is probably the most effective route.
Figure 5: Possible Production by Technologies in 2020 and 2030

Source: Strategies Unlimited
Visions for PV 1

Table 2. Key cost and investment assumptions of renewables. Source: IEA, 2006

<table>
<thead>
<tr>
<th>Solar Resource</th>
<th>Learning rate (%)</th>
<th>Investment cost ($/kW) 2005–2050</th>
<th>Production cost ($/MWh) 2005–2050</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>2005</td>
<td>2030</td>
</tr>
<tr>
<td>Geothermal</td>
<td>5</td>
<td>1700–5700</td>
<td>1500–5000</td>
</tr>
<tr>
<td>Large hydro</td>
<td>5</td>
<td>1500–5500</td>
<td>1500–5500</td>
</tr>
<tr>
<td>Small hydro</td>
<td>5</td>
<td>2500</td>
<td>2200</td>
</tr>
<tr>
<td>Tidal</td>
<td>5</td>
<td>2900</td>
<td>2200</td>
</tr>
<tr>
<td>Wind onshore</td>
<td>5</td>
<td>900–1100</td>
<td>800–900</td>
</tr>
</tbody>
</table>

Note: Using a 10% discount rate. The actual global range is wider as discount rates, investment cost and fuel prices vary. Wind and solar include grid connection cost. Learning rate implies percentage cost reduction for each doubling of installed capacity.
Visions for PV 2

- Japan 2030:
  - 52-82 GW installed
  - 5-10 Yen/kWh

- USA 2030:
  - 25 GW installed (10 % of electricity)
  - 150,000 new jobs

- EU 2010:
  - 3 GW installed (1 % of el.) – expect. > 6 GW
# Visions for PV 3

Extract from the roadmap developed by representatives of industry and research at the 9th Glattal talks

<table>
<thead>
<tr>
<th></th>
<th>As at 2005</th>
<th>Target 2010</th>
<th>Target 2020</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Economy</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Capacity produced in Germany (MWp/a)</td>
<td>350</td>
<td>1,000</td>
<td>12,000</td>
</tr>
<tr>
<td>Jobs in Germany</td>
<td>20,000</td>
<td>50,000</td>
<td>200,000</td>
</tr>
<tr>
<td>System price (grid-connected, euro/W)</td>
<td>4.5 – 5.5</td>
<td>3.6</td>
<td>1.5</td>
</tr>
<tr>
<td>Photovoltaic electricity costs in Germany (Cent/kWh)</td>
<td>45 (±/-5)</td>
<td>30</td>
<td>10</td>
</tr>
<tr>
<td>Module life (years)</td>
<td>20 – 25</td>
<td>35</td>
<td>35</td>
</tr>
<tr>
<td>Inverter (euro/Wp)</td>
<td>0.4</td>
<td>0.2</td>
<td>0.15</td>
</tr>
<tr>
<td><strong>Wafer technology</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Silicon requirement (t/MW)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Foils</td>
<td>8</td>
<td>6</td>
<td>5</td>
</tr>
<tr>
<td>• Block-casting</td>
<td>12</td>
<td>10</td>
<td>5</td>
</tr>
<tr>
<td>Wafer thickness (µm)</td>
<td>250 – 300</td>
<td>150 – 180</td>
<td>100</td>
</tr>
<tr>
<td><strong>Cell efficiency in production</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wafer technology</td>
<td>16.5</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>• Monocrystalline</td>
<td>14 – 14.5</td>
<td>17 – 18</td>
<td>20</td>
</tr>
<tr>
<td>• Polycrystalline</td>
<td>9</td>
<td>12</td>
<td>15</td>
</tr>
<tr>
<td>Thin film silicon</td>
<td>10</td>
<td>14</td>
<td>17</td>
</tr>
</tbody>
</table>

Solar Energy – Status & Perspectives
PA Energy A/S
Cost & Prices
Price 2006: 0.5 US$/kWh (OECD aver.)

Levelized cost of solar power - 2006

Source: Photon Consulting

Solar Power – Status & Perspectives
PA Energy A/S
Cost Reduction Drivers

Cost reduction drivers through 2010

Source: Photon Consulting
Technical Potential Solar

Electricity: 323 km² (@ 360 TJ per km²)
Energy: 2260 km²
PV’s in Transport?

Distance reached with 1 ha of energy crop / PV ground-mounted system

- Biodiesel *3: 21,500 km
- Bioethanol (from wheat) *2: 22,500 km
- Biomass to liquid *3: 60,000 km
- Biogas (from corn) *2: 67,000 km
- Electricity (Plug-in Hybrid operation) *1: 3,250,000 km

1 ha is equal to 100 x 100 m or 10,000 m². An average-sized soccer field is 0.75 ha.

*1 Average usage 16 kWh/100 km
*2 Average usage 7.4 l/100 km fuel equivalent
*3 Average usage 6.5 l/100 km fuel equivalent

Source: Photon
World Wide Access to Electricity
Developing Countries – “the dark locations”
Energy and Development –

a new understanding

• Access to energy and electricity does not create development but is a prerequisite for development. Energy is not only an individual sector, but:

• Energy and electricity is a precondition for efficiency in public sectors such as: health, education, water & sanitation, good governance/democracy

• Energy and electricity is a precondition for progress in poverty alleviation, equality, justice etc.

• Energy is a precondition in reaching the Millennium Development Goals
WBG Photovoltaic Projects

Serving >1,43 million HH + Facilities  ~7.5 million persons
~64 MWp  31 Countries  Total Value: ~$776 million

Argentina 30,000
Bolivia 60,000
Ecuador 2,200
Honduras
Dominican Rep.
Mexico 1,000
Mexico 36,000
Nicaragua 6,000

Includes projects completed, under implementation and preparation

Burkina Faso 8,000
Cape Verde 4,500
Ethiopia 6,300
Kenya
Madagascar 15,000
Mali 10,000
Morocco
Mozambique 9,800
Senegal 10,000
Swaziland 2,000
Uganda 90,000
Tanzania 140,000

Bangladesh 198,000
Cambodia 10,000
China 400,000
India 45,000+
Indonesia 8,500
Laos 4,000
Mongolia 50,000
Pacific Islands 21,000
Philippines 135,000
PNG 2,500
Sri Lanka 105,000
Vietnam
Challenges for Solar Energy

• In the industrialized world:
  – To ensure ongoing market support until sustainable business level is reached
  – Ongoing R&D effort (not stop/go)
  – Up-scale production to GW scale, volume a major cost reduction driver

• In the developing world:
  – Develop financial structures and sustainable supply chains
  – Increase donor-support for rural electrification
Solar Hot Water systems (SHW)
Solar Heating Applications

Solar cooling & heating system: demand & supply

- Solar collector yield
- Domestic hot water demand
- Space heating demand
- Cooling demand

Solar thermal can cover a substantial part of the heating and cooling demand in a typical Central European building.
SHW Market
SHW installed capacity in EU

[Diagram showing the share of solar thermal market in the EU, indicating countries such as Germany, Austria, and others with their respective shares.]

[Another diagram showing the installed capacity per capita across EU countries, with a bar graph indicating varying capacities and a note stating that the countries not shown have even lower values than Ireland.]
Trends & Policies