Electricity Saving Possibilities in Household and Office Appliances

Kotitalouksien ja toimistotilojen laitesähkön käytön tehostaminen

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Abstract

The task was to assess the penetration of new technology and its effects on energy efficiency by the year 2010 in the electricity consumption of appliances and lighting in households, excluding leisure time dwellings, in offices and in the service sector. Heating of premises and water was excluded. The work was based on secondary analysis. The BAU scenario showed that in Finland refrigeration appliances and lighting will consume the biggest shares of household electricity in 2010, followed by cooking, sauna, and consumer electronics, which will increase proportionally most. By using the existing best energy efficient technologies, not always economically feasible, the expected consumption will decrease, *e.g.* that of consumer electronics by 20%, of lighting by 65%, and of refrigeration by 14% compared to the BAU scenario. Refrigeration appliances will still consume the biggest share. In the area of lighting, adoption of the best technical solutions will produce bigger savings in consumption than in other areas altogether. However, accounting for the additional heat the appliances and lighting are producing, the technically possible savings, 2 050 GWh/a, of household electricity in 2010 will decrease by 15%, and increase non-electric heating energy by 580 GWh/a.

In offices, electricity consumption of 720 GWh/a of present equipment is quite possible to be decreased by 30%, by utilizing the power management of the appliances. Compared to the BAU scenario, it is possible yearly to save 480 GWh/a, 67% of the consumption of the office equipment, and 690 GWh/a, 75% of the consumption of lighting by the year 2010 by using the best technologies in all offices. Calculations on the office equipment are based on present consumption and on present best technologies. Savings in consumption of lighting are based on estimations on office premises in 2010 and on the presumption of using the best technologies in all uses. This development will, on one hand, indirectly decrease energy consumption of ventilation, but on the other hand, increase the need of non-electric space heating energy. Calculations by the Reduce-model showed that CO_2 emissions from household electricity obviously will not – by 2010 – be lowered into the level before 2000, which was 1,6 million tons/a. In offices, CO_2 emissions of the appliances including lighting will stay (in the BAU scenario) at 0.3 million tons/a in 2010, which is nearly the same level as in the year 2000.

Tiivistelmä

Tavoitteena oli selvittää kotitalouksien ja toimistojen sähkölaitteiden teknologian ja käytön tehostamismahdollisuuksia vuoteen 2010 mennessä. Työ rajattiin kotitaloussähköön, toimistotilojen valaistukseen ja sen ohjausjärjestelmiin sekä tieto- ja toimistotekniikkalaitteisiin. Loma-asunnot, sähkölämmitys ja lämpimän käyttöveden valmistus eivät sisälly tutkimukseen. Kotitaloussähkön kulutuk-

sen normaalikehitys (BAU) osoittaa, että kylmäsäilytys ja valaistus tulevat olemaan suurimmat kulutustekijät. Seuraavina tulevat kulutuselektroniikka, ruoanvalmistus ja sähkösauna. Teknisesti jo mahdollinen kehitys, joka ei kaikkien laitteiden osalta ole taloudellisesti kannattava, vähentää kulutuselektroniikan sähkönkulutuksesta noin viidenneksen, valaistuksesta lähes kaksi kolmasosaa ja kylmäsäilytyksestä vajaan seitsemäsosan normaalikehitykseen verrattuna. Valaistuksen teknisesti mahdollinen kehitys tuottaa suuremman säästön valtakunnallisesti kuin kaikkien muiden tekijöiden vaikutus yhteensä. Sähkölämmitetyissä asunnoissa osa laitelämmöstä hyödynnetään lämmityksessä. Kun se otetaan huomioon, teknisesti mahdollinen sähkön kokonaissäästöpotentiaali (2 050 GWh/a vuonna 2010) pienenee noin 15 %:lla arvoon 1 740 GWh/a. Muissa kuin sähkölämmitetyissä asunnoissa lämmitysenergian tarve kasvaa noin 580 GWh/a.

Sähkönkulutuksen kannalta parhaan teknologian käyttöönotto kaikkien rakennusten toimistotiloissa vuoteen 2010 mennessä mahdollistaisi 67 %:n vuotuisen sähkönsäästön (479 GWh/a) toimistotekniikkalaitteiden ja 75 %:n sähkönsäästön (693 GWh/a) valaistuksen kulutuksessa normaalikehitykseen (BAU) verrattuna.

Todennäköisesti kotitalouksien laitesähkön käytön aiheuttama hiilidioksidimäärä ei vuoteen 2010 mennessä ehdi laskea alle vuoden 2000 tason. Toimistojen laitesähkön kulutuksen aiheuttamat hiilidioksidipäästöt ovat BAU-skenaariossa 0,3 miljoonaa tonnia vuonna 2010, mikä on lähes sama kuin vuonna 2000.

1 Introduction

1.1 Background

Our objective in Finland, as a member of the European Union, is to restrict the emissions of greenhouse gases so that the average annual emissions during the first commitment period of the Kyoto Protocol 2008–2012, will not exceed the level of 1990, equivalent of about 76.5 tons of carbon dioxide. Measures to obtain this goal are given in our national Climatic Strategy, in which emphasis is given on increasing efficient use of energy and on improving energy saving technologies (Government 2001).

In statistics, energy consumption of dwelling includes households and houses, leisure time houses and farm-houses. According to Statistic Finland the consumption was about 12.2 TWh in 2000, and the shares of consumption were: households about 9 TWh, dwellings about 1.8 TWh, leisure time houses about 0.5 TWh and farm-houses about 0.8 TWh. Electric heating of dwellings, which consumed roughly 6.9 TWh in 2000, is not included.

The service sector includes trade and shops, hotels and restaurants, transportation, storing, data communications, banking, management for estates and business, and other private and public services. According to Statistic Finland the energy consumption of service sector was about 12.5 TWh in 2000.

1.2 Aim and outlining

The task was to assess possibilities to increase efficiency in technology and in the use of electrical appliances in household and service sectors. The aim was to figure the potentials of efficiency by the year 2010 with consideration of economical and environmental effects, especially impacts on CO_2 emissions.

In the field of dwellings this report focuses on its biggest share, consumption of household electricity. This report will not deal with space and water heating. In the field of services this report focuses on the office equipment and lighting, which cover about 40% of the total electricity consumption in offices (about 4,1 TWh in 2000).

Electricity consumption of appliances means here the electric energy supplied from power grid to an electric appliance. Heat generated by an electric appliance has been partly reckoned in calculations.

2 Methods

The first stage was to assess the state of art of technology in use. Bottom-up calculations were used. Concerning households the present penetration of each appliance group in households and the average consumption based on tests or manufacturers' claims were used to reach the total household electricity consumption, which was 9 035 GWh, in 2000 according to Statistics Finland. The calculated shares of appliance groups were subtracted from the total giving the remainder, "miscellaneous". In addition, the level of electricity consumption of the best technology on the markets was gathered.

Concerning office equipment the level of electricity consumption of the selected equipment groups was gathered based on figures from different countries.

The second step was to assess the penetration of new technology of each appliance group within the coming 10 years and its effect on energy savings. This was done by using the Reduce-model.

The third stage was to assess the electricity saving potential and its effect on CO_2 emissions in Finland between BAU- and saving scenarios in these two sectors by the year 2010.

3 Electricity consumption of household appliances and saving potentialities

3.1 Development in general

In 2000 the largest consuming groups were refrigeration appliances, cooking, consumer electronics, and lighting, and three of the first groups will still stay as the largest ones by 2010 (Table 1) even in the energy saving scenario.

Consumption in 2010 was forecast mainly based on two scenarios. Business as usual (BAU) means that no new means will be implemented to improve energy efficiency. In "Technically possible" scenario it was assumed that only the best technique will be bought. The BAU-scenario resulted in 9 544 GWh in 2010. The technically possible scenario represented 21.5% declining consumption being about 7 500 GWh in 2010.

Table 1. Shares of household electricity consumption in 2000 and in 2010, and the saving potential.

Appliances	**2000**	**2010**		
	GWh/a	**BAU, GWh/a**	**Techn., GWh/a**	**Saving pot., GWh/a**
Refrigeration appl.	2 216	1 710	1 455	255
Consumer electronics	1 080	1 545	1 162*	383
Cooking	1 156	1 265	1 169*	96
HVAC (one-family h.)	438	550	455	95
Car heating (one-family h.)	146	200	200	0
Washing machines	570	444	398	46
Textile dryers	107	145	114	31
Dishwashers	330	246	229*	17
Sauna stove	807	1 000	1 000	0
Lighting (indoor+out.)	1 617	1 747	618	1 129
Miscellaneous	568	692	692	0
All	**9 035**	**9 544**	**7 492**	**2 052**

* economically feasible

3.2 Development by appliance groups

3.2.1 Refrigeration appliances

In spite of increasing amount of refrigeration appliances, their share of electricity consumption seems to decrease by 2010 by both scenarios. If neither the new energy-labelling nor other means to improve the energy efficiency of refrigeration appliances will not be implemented, their estimated consumption will be 1 710 GWh in 2010. The consumption will be even as low as 1 455 GWh, if only the most energy efficient fridges and freezers were bought, in addition to all new fridge-freezers being Energy+ -appliances. The saving between this scenario and the BAU-scenario is about 255 GWh/a.

3.2.2 Cooking

The number of households will increase by the year 2010. The use of a cooker and a microwave oven is supposed to stay at the present level. This is the reason for increasing energy consumption of cooking in both scenarios.

The BAU-scenario supposes that the consumption of ovens and microwave ovens will remain unchanged, but that of hobs will decrease a bit when ceramic hobs are becoming more general. This all will result in cooking about 1 265 GWh in 2010.

The technically and economically feasible scenario assumes that in addition to more general ceramic hobs, the standby power of microwave ovens will lower from 4 W to 1 W, and all new ovens will consume 20% less than the present average (Kasanen 2000). This will result in cooking about 1 169 GWh in 2010. The saving between this scenario and the BAU-scenario is about 96 GWh/a.

3.2.3 Dishwashers

Water and electricity consumption have decreased remarkably since 1990. In the coming years this development will slow down, because no significant new technique is in horizon (GEA 1995). The total consumption will decrease in spite of higher penetration, because the new appliances are much more energy efficient.

In the BAU-scenario, dishwashers will consume in 2010 about 246 GWh. If all new dishwashers were of A-class in energy efficiency (technically and economically feasible scenario), they would consume about 229 GWh in 2010, and the saving between this scenario and the BAU-scenario would be 7%.

3.2.4 Washing and drying textiles

Electrical drying is becoming more general resulting in increasing energy consumption in all scenarios in spite of decreasing special consumption of tumble dryers. Cabin type of dryers will remain at the present level of energy efficiency, but that of washing machines will decrease compared with the present level.

In the BAU-scenario, electricity consumption of washing machines will be 444 GWh and that of drying about 145 GWh in 2010, 589 GWh together.

The technically possible scenario assumes that all new washing machines and all tumble dryers will be of the best new technology. In this case the washing machines will consume about 398 GWh and the electrical dryers about 114 GWh in 2010. The saving between this scenario and the BAU-scenario is over 10% GWh.

3.2.5 Consumer electronics

Electricity consumption of consumer electronics including phones etc. was calculated to be 1 080 GWh in 2000. Per one household it means 453 kWh, and a half of it goes to different standby modes.

The BAU scenario assumes that the whole stock of appliances, excluding stereo- and other audio-appliances, will be replaced by new techniques in 2001…2010. In this case the electricity consumption of the group, including phones, will be about 1 545 GWh, of which the standby consumption will be about 800 GWh (308 kWh/a/household).

Electricity consumption of ADSL- and cable modems making wide band internet connection possible are not included in the total consumption, because the technology of arranging the connections has not been defined yet. If the connections will be arranged by other means than TV digital boxes, consumption of household energy will increase.

The electricity saving scenario is also based on the assumption that in 2001…2010 the whole stock of equipment, excluding stereo- and other audio-equipment will be renewed, and all consumer electronics will be energy efficient and fulfil GEEA requirements (GEEA 2002).

These assumptions take off nearly half of the standby-consumption, which will thus be 450 GWh/a. New technology stereos will also consume about 50% less than the present ones, saving 99 GWh. TV digital boxes seem to give the biggest saving, but only with reservations, because this kind of equipment is under constant development and the whole stock will be renewed. Decrease of electricity consumption will mainly be due to the development in standby power consumption technology.

3.2.6 Lighting

Lighting represented some 18% of the household electricity consumption in 2000, corresponding absolute annual consumption of 1 617 GWh.

This figure includes outdoor lighting of one-family houses, but no other houses, where lighting is a component of the electricity consumption of the estate.

In the BAU-scenario the share of lighting in electricity consumption will increase to 1 747 GWh by the year 2010. According to the realistic saving scenario, the amount of compact fluorescent lamps (single-capped and self-ballasted fluorescent lamps) per household will be increased from two (BAU) to six by the year 2010. In this case the electricity consumption of lighting will be 1 368 GWh in 2010. The saving between this scenario and the BAU-scenario is about 379 GWh/a (22%).

With the existing technique, the most remarkable saving would be achieved by changing all incandescent lamps to fluorescent lamps. This would decrease the share of lighting in 2010 to as low as 618 GWh, and the saving would be 1 129 GWh/a (65%) compared to the BAU-scenario.

3.2.7 Sauna

The share of saunas with an electric stove of the household electricity consumption was about 807 GWh in 2000. The number of saunas with an electric stove will increase by the year 2010, because nearly all of the new dwellings will be equipped with a sauna. The amount of constantly supplied electric stoves will increase. In 2010 the saunas will consume nearly 25% more than nowadays.

3.2.8 HVAC-systems

In 2000 the HVAC-systems in one-family houses consumed about 438 GWh, which is included in the household electricity consumption. It should also be noted that nowadays it is a trend to install even in blocks of flats and in terrace-houses ventilation systems per a flat, and the electricity needed to use it will be included into the household electricity consumption.

In the BAU-scenario, the share of ventilation in one-family houses will increase proportionally a lot by the year 2010, because the annual amount of new small houses will be about 10 000, and they will be furnished with automatic ventilation systems.

This development will increase the electricity consumption of ventilation by 90 GWh in 2010 to a total consumption of about 248 GWh.

In the saving scenario, technically possible, the ventilation fans will be equipped with good efficiency DC motors, and different pumps will be equipped with adjustable speed control.

In the case that all one-family houses, furnished with air-conditioning and heat recovery, will be equipped with DC motors in 2010, and saving achieved would be 30% compared to conventional frequency converters, the saving in electricity consumption would be about 56 GWh, and the total share of ventilation would be 192 GWh.

Pumps of oil-fired boilers and drill well pumps as well as building automation belong to the HVAC-systems, but here they are dealt with the energy consumption of “miscellaneous”.

3.2.9 Miscellaneous in household energy including block heaters

In 2000 the share of miscellaneous in household energy was about 568 GWh. It will increase to 692 GWh by the year 2010.

The block *etc* heaters for cars took in 2000 about 146 GWh of the household electricity consumption. This share will increase to about 200 GWh by the year 2010, because these heating systems are standard equipment of new cars.

3.3 Electricity of appliances and space heating

Electricity used by the appliances finally converts to heat and during the heating period it can partly be utilized for space heating. The type of the building, its ventilation and heating systems as well as the timing of the heat loads are decisive for the extent of utilisation of this converted heat.

Lighting is mainly used during heating season and in all spaces of the dwelling. That's why the heat from lighting can best be utilized, especially in houses with direct electric heating and with sensitive thermostats in addition to air-conditioning and heat recovery.

Because of the need to compensate in space heating the decreased heat from energy efficient appliances, the electricity saving potential in the saving scenario needs to be corrected from 2 052 GWh/a in 2010 to 1 713–1 761 GWh/a. The efficiency used in the calculations was 60–77% for lighting and 50% for appliances. Additional heating energy will be about 580 GWh/a, increase of one third for houses with heating systems other than direct electricity.

3.4 Electricity saving potentials of household appliances

Consumption of household electricity in 2010 will be about 9 500 GWh or about 7 500 GWh depending on the scenario. The total electricity saving potential is about 2 050 GWh/a, but after correction for heating 1 713–1 761 GWh/a.

Lighting offers the biggest potential, over 50%, followed by refrigeration appliances and consumer electronics (Table 2).

Some of these potentialities are not economically profitable, yet. However, for penetration of efficient consumer electronics and cooking, even dish-

Table 2. Electricity saving potentials of household appliances in 2010.

Appliance	Saving potential, GWh/a	Corrected saving potential, GWh/a	% of the total saving potential
Refrigeration appliances	255	223	12.7–13.0
Consumer electronics	383	335	19.0–19.6
Cooking	96	84	4.8–4.9
HVAC-systems *	95	76	4.3–4.4
Car heating *	0	0	0
Washing machines	46	40	about 2.3
Dryers (tumble-, cabin-)	31	27	1.5–1.6
Dishwashers	17	15	about 0.9
Sauna	0	0	0
Lighting (indoor+outdoor)	1 129	913...961	53.3–54.6
Miscellaneous	0	0	0
All	**2 052**	**1 713...1 761**	**100**

*one family houses

washers, there are no economical barriers any more. *E.g.* in consumer electronics the price of energy efficient technique or components is not higher than that of the less efficient, but they are only installed in more expensive appliances. In cooking the potential is technically and economically profitable according to the SAVE-project (Kasanen 2000), including decreased standby power in microwave ovens, which is economical, too. In dishwashers the best options according to the GEA-project are now a reality (GEA 1995).

By refrigeration appliances with the least life cycle costs, also economically realistic, it would be possible to achieve in 2010 one fifth of the saving of the technically possible scenario.

By washing machines with economically profitable life cycle costs, it would be possible to achieve in 2010 one tenth of the saving of the technically possible scenario. Concerning dryers, the technically possible option, the heat pump, is still economically unrealistic. However, one third of its efficiency would be achieved by using washing machines with high spin efficiency, which, on the other hand, are not always profitable for consumers, because spin efficiency is often linked with price. So, it is the patterns of use, which are decisive; less runs with full load and lower washing temperatures.

To achieve the saving potential of about 900 GWh in lighting in 2010 would require changing all incandescent lamps to fluorescent lamps, which is unrealistic. It is realistic to increase the number of compact fluorescent lamps from two (BAU) to six per a household by the year 2010. This would give a saving of about 380 GWh/a.

4 Reduce model

The Reduce is a socio-economical model including statistical analyses (Krujk et al. 1997). It is useful to figure the penetration of energy efficient appliances and actions into the market, in addition to sectors of economics with certain restrictions. In this project it was used to examine the household electricity consumption and saving in connection with different energy efficient household appliances.

Energy labelled household appliances were a good starting point for the use of the Reduce model offering a distinct option when renewing a household appliance. Refrigeration appliances were examined in three groups, and good examples were dishwashers and washing machines as well as lighting. Electricity consumption in these groups could be shown to decrease.

Market penetration of an energy efficient appliance is subject to the provision that the appliance price is optimal compared to the saving achieved; low enough to the household and high enough to the manufacturer. One example is the penetration of the compact fluorescent lamp, which has been on the market for a long time, but without any bigger market share. Its price is about 10 euro and penetration in 2000 only few per cents. The Reduce model showed that decreasing the price to 3,4 euro would increase its penetration to 80%, which would lower electricity consumption of lighting to one third from the present one by the year 2010.

According to the Reduce model, fridges of C class, which are quite energy efficient but with only moderately higher prices, will take a big market share. But even removing appliances of this class from the market in order to enhance fridges of A or B class would not increase electricity saving by the year 2010.

Consumer behaviour in energy saving seems not be optimal in general. It would be economically clever to be more active to choose an energy efficient appliance instead of the conventional one. However, it is not beneficial for electricity saving in total to produce more efficient, but too expensive appliances. And it is not economical to change an old but still operating appliance to a modern one.

Moderate price development of electricity does not affect on electricity consumption in households; an increase of 50% in the price level would be needed to achieve a remarkable increase in motivation to electricity saving.

New measures would be needed to lower the electricity consumption under the level of 2000 by the year 2010. In any case, the development of electricity consumption will stay lower than that of GNP.

5 Electricity consumption of office equipment and energy saving potentialities

This project examined two of the most significant groups in offices: office equipment and lighting.

Calculated consumption of these groups in the years 2000 and 2010 are represented in Table 3. They covered about 39% of the total electricity consumption of offices and administration, which was 4 094 GWh (in 1998).

Office equipment includes PC work stations with servers, printers and copy machines.

Electricity consumption of all office equipment and telecommunication was estimated to be about 1 TWh in 2000. Saving potential of office equipment will be 251 GWh in 2010, if the power management would be utilized to 100%. To achieve the total electricity saving potential of 1 172 GWh in 2010 means that all existing best technology would be used in all offices. This development would increase the need of non-electric heating by about 410 GWh/a.

This saving potential is very theoretical. In lighting it would require the best techniques in all offices. In this case the electric power would be 5 W/m^2, occupancy sensors would decrease the annual consumption by 15% and an automatic lighting control system including daylight compensation by additional 10%.

Concerning office equipment the saving potential is more real, because nearly the whole stock will change to new ones by the year 2010. In addition, decreased electricity consumption will indirectly decrease the electricity consumption of ventilation. In this group of office equipment the products are developing rapidly. Real possibilities for electricity saving could be achieved by selecting the most efficient appliances and adjusting the right settings and power managements. However, to find the best solutions, monitoring and new research is needed.

90% of electricity consumption of copy machines and printers is due to standby consumption. The users normally don't adjust the power management system. Measurements of this project showed that optimising the set values could decrease electricity consumption of copy machines even as much as 25%. Multi Function Devices combining different operations would decrease the amount of equipment resulting in a decrease in standby consumption as well.

Table 3. Electricity consumption in the scenarios and saving potential in offices.

Equipment group	2000 (GWh)	2010 BAU (GWh)	2010 Technically possible (GWh)	Saving potential 2010 (GWh)
Office equipment	719	719	240	479
Lighting	890	927	234	693
All	**1 609**	**1 646**	**474**	**1 172**

6 CO_2 emissions of household appliances and office equipment

The calculations were based on the assumption that the environmental impact of the electricity generated for households is similar to that in Finland in general. Kyoto 1 scenario (MTI 2001), the scenario of electricity generation based on natural gas, was used, and assessments were made on the timing and the rate to limit the use of condensing coal-fired power plants and on the net imports of electricity. The average emissions of electricity generation in Finland were used (Lehtilä 2002).

The trend is ascending/increasing for some years before the measures to limit emissions start to influence, decreasing special emissions. In the year 2010 the level of 2000 would be achieved.

CO_2 emissions of household electricity consumption for the years 2000–2010 were calculated based on 5 scenarios. Biggest emissions resulted in a scenario based on GNP, and the least on the Technically possible scenario. The others, the Reduce model, the BAU-scenario and the BAU trend-estimation method, gave nearly the same results, which were obtained between the two former ones. It seems that the CO_2 emissions of household electricity consumption cannot reach the level lower than in 2000, about 1.6 million tons, by the year 2010. The BAU-scenario and the scenario representing the amount of dwellings are showing the level of 1.8 million tons, and only by special measures for energy saving 1.6 –1.8 million tons could be a realistic target in 2010.

The CO_2 emissions of electricity consumption of office equipment will be 0.3 million tons/a in 2010 according to the BAU scenario. Theoretically it would be possible to decrease it to as low as 0.09 tons/a, but the realistic target is 0.2 tons/a in 2010.

7 Discussion and conclusions

In the calculation, many assumptions and generalisations have been used, which are causing uncertainty of the results. Even the household electricity consumption of the base year, 2000, has been estimated since the last measured data originates from 1993. Refrigeration appliances are taking the biggest share, and even that might be underestimated, because we had no statistics about the amount of so called “second appliances”, mostly freezers and often the older ones. The present 14 years was used as the life time of the refrigeration appliances, but fridge-freezers on the market are shifting to models with only one compressor, which usually gives lower energy consumption, but its influence on the life time has not been proven.

The trends of food management, home made or ready meals or even eating outside of home, is very sensitive to the economical and social factors. International food chains are also penetrating in Finland.

Energy labelling of washing machines and dishwashers has gradually changed the programs meant for this testing to be more time consuming to ensure good energy efficiency and washing results. Calculations are based on these programs, but consumers might shift to different “rapid” programs, which often are less energy efficient.

Standby modes might become more general than expected and increase electricity consumption. On the other hand, smart appliances might become more general, too, and decrease electricity consumption.

Publications and reports made under the project

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Generating CO_2 Emission Reductions through Energy Service Companies (ESCOs)

Energiapalveluyhtiöiden (ESCO) toiminta ilmastonmuutoksen rajoittamisen näkökulmasta

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Abstract

The business model of Energy Service Companies (ESCOs) is a solution to the financial and human resource problems in improvement of energy efficiency. Investments in energy efficiency often simultaneously reduce greenhouse gas (GHG) emissions. The objectives of the CO2ESCO project were: (i) to assess in what kind of projects the ESCO-concept is appropriate and what is its potential to reduce GHG emissions; and (ii) to explore, whether the emission reductions generated through various projects can support ESCOs and which measures are required for the utilisation of this potential. This paper first discusses the estimation of emission reductions associated with ESCO projects. Second, the integration of emission reductions into ESCO projects is examined. Third, an ESCO market potential and the respective GHG abatement potential in the Finnish industry is estimated. The market potential of ESCOs is estimated at 1 890 GWh/a heat and 340 GWh/a electricity. The required investment is around 200 million €. The GHG abatement potential is estimated at 0.3–0.4 Mt CO_2 /a. The results show that emission reductions do not seem to emerge as a driving force for most ESCO projects. However, they can generate some extra cash flow, if transaction costs remain at a reasonable level compared to benefits. Industrial ESCO projects in Finland to cut the consumption of electricity and those to cut the consumption of heat are in a very different position, when it comes to GHG abatement. Any conclusions on the implementation of the GHG abatement potential depend decisively on the approach to the emission intensity of electricity.

Tiivistelmä

Energiapalveluyritysten (myös: ESCO) liiketoimintamalli on yksi ratkaisu energiansäästön rahoitus- ja henkilöresurssiongelmiin. Energiansäästöinvestoinnit vähentävät usein myös kasvihuonekaasupäästöjä. CO2ESCO-projektin tavoitteina oli (i) selvittää, millaisiin hankkeisiin ESCO-konsepti sopii Suomessa ja millainen kasvihuonekaasupäästöjen vähentämispotentiaali ESCO-hankkeisiin liittyy sekä (ii) selvittää, voivatko hankkeiden yhteydessä syntyvät päästövähenemät tukea energiapalveluyhtiöiden toimintaa ja mitä toimenpiteitä päästövähenemien hyödyntäminen edellyttäisi ESCO-yrityksiltä ja viranomaisilta. Tässä artikkelissa tarkastellaan ensin päästövähenemien suuruuden arviointia ESCO-projekteissa. Seuraavaksi tarkastellaan päästövähenemien integrointia ESCO-sopimuksiin. Kolmanneksi arvioidaan ESCO-hankkeiden markkinapotentiaali Suomen teollisuudessa ja sen vaikutus kasvihuonekaasupäästöihin. Markkinapotentiaaliksi saatiin 1 890 GWh/a lämpöä ja 340 GWh/a sähköä. Vaadittava investointi on noin 200 miljoonaa €. Kasvihuonekaasujen vähentämispotentiaali on noin 0,3–0,4 Mt CO_2/a. Työn tulokset osoittavat, etteivät päästövähenemät todennäköisesti muodostu useimmissa ESCO-hankkeissa toteutuksen ratkaisevaksi tekijäksi. Niiden avulla voidaan kuitenkin luoda lisäkassavirtaa, jos hankkeiden transaktiokustannukset pidetään alhaisina suhteessa saavutettavaan hyötyyn. Kasvihuonekaasupäästöjen vähentämisen näkökulmasta ESCO-hankkeet lämmön ja sähkön säästämiseksi teollisuudessa ovat hyvin erilaisessa asemassa. Johtopäätökset hankkeiden lämmön- ja sähkönkulutuksen vähentämisen päästövaikutuksesta riippuvat ratkaisevasti tavasta lähestyä sähkön päästöintensiteettiä.

1 Introduction

The business model of Energy Service Companies (ESCOs) is a solution to the financial and human resource problems of energy efficiency improvement, which often prevent or postpone investments in energy efficiency. ESCOs make an energy performance contract with the client, in which the ESCO commits itself for delivering a turn-key-project to the client. The ESCO is responsible for the planning, implementation, financing and operation of the project. The investment is amortised through the energy cost savings it generates.

Investments in energy efficiency often simultaneously reduce greenhouse gas (GHG) emissions. As climate change mitigation seems to create a market for emission allowances and reductions, emission reductions generated in ESCO projects may become an additional factor that must be taken into account in project planning and implementation.

The objectives of this study were: (i) to assess in what kind of projects the ESCO-concept is appropriate and what is its potential to reduce GHG emissions; and (ii) to explore, whether the emission reductions generated through projects can support ESCOs and which measures are required for the utilisation of this potential.

This paper is an executive summary of the CO2ESCO project managed by Motiva Oy and primarily implemented by Electrowatt-Ekono Oy within the framework of the Climtech programme administered by Tekes, the National Technology Agency in Finland. The key results of the project are structured here as follows:

- estimation of emission reductions in ESCO projects
- integration of emission reductions into ESCO projects
- GHG abatement potential with ESCOs in Finnish industry.

2 Estimation of emission reductions

Emission reduction refers to the reduction in emissions achieved through the project in comparison with the *baseline*, an emission scenario without the project. In energy efficiency projects, the estimation of emission reductions can be made in two phases: i) estimation of the energy saving and ii) estimation of the emission intensity of the energy saved. The first phase is an integrated part of any ESCO project.

In this project, estimation of emission intensity for the energy saved in a given ESCO project was studied in three distinct cases: i) heat savings from a heat only plant; ii) electricity savings; and iii) heat savings from a combined heat and power (CHP) plant. At least two different levels can be distinguished in this kind of analysis: impacts on the company studied and impacts on the energy system as a whole. The latter was selected as the basis for the analysis.

Heat savings from a heat only plant should be analysed project-specifically. The project boundary should cover the heat generation system. If there are several plants with distinct features, their dispatch order should be taken into account in the determination of the emission intensity. The time dimension of the intensity should rely on a scenario that is based on the techno-economic lifetime of the boilers. If the system is simple and stable, the baseline emission intensity may be fixed. In the case there are several plants using different fuels, a revisable level of baseline emission intensity may be considered.

Emission intensity of electricity should be generic for a given grid. In Finland an appropriate project boundary is the country as a whole or even a larger area, such as the Nordpool region. Several studies (e.g. Kartha et al. 2002, Holttinen and Tuhkanen 2002, Ellis et al. 2001, OECD/IEA 2000) suggest that average emission intensity often badly reflects the actual impact on the electricity system, as power plants are typically dispatched according to their variable production costs. Variable production costs are low for GHG-free nuclear and hydro power. Therefore, emission intensity should be estimated on a marginal basis. National scenarios can be used ex-ante and the emission intensity can be revised during the project lifetime.

In the case of combined heat and power generation, the two previous cases must be combined. It is essential to take into account the potential impact of heat saving on electricity production of a CHP plant.

3 Integration of emission reductions into projects

Emission reductions can have a role in ESCO projects only if they have a value. The value for emission reductions can arise in several ways depending on the policy instruments used in national and/or international climate policy. For example, taxation based on carbon dioxide (CO_2) emissions would increase the feasibility of energy efficiency projects in which the energy saved is CO_2 -intensive. However, since the tax is included in the price of energy, the integration of the corresponding benefit would not set any additional requirements on ESCO projects.

In the case of an emissions trading system, the situation would be more complicated. An emissions trading system would create a market price for CO_2-reductions. The emission reductions of ESCO projects would need to be taken into account by the project parties themselves.

Recent estimates (e.g. Natsource and GCSI 2002) on the evolving market price for emission reductions are lower than those immediately after the Kyoto Protocol. This can be traced, e.g., to the results of COP7 in Marrakesh in November 2001 and the decision of the United States not to ratify the Kyoto Protocol. A value of 5 €/tCO_2 would not have a significant effect on the viability of ESCO projects to conserve heat. The impact would be larger, if electricity generation from a CHP plant was not affected and the fuel used in heat production was emission intensive. In electricity projects, the impact would be significant, if marginal emission intensity was applied.

Estimation of emission reductions is not always straightforward. Thus the integration of emission reductions in ESCO projects would include some additional transaction costs. Additional activities needed in the case of an emissions trading system (either a *cap-and-trade* or a *baseline-and-credit* system[1]) include the specification of the project boundary, emission reduction, emission intensities, possible updating of the baseline, monitoring and possible validation, verification and reporting.

Project boundary

If only direct emissions of a site are included in the relevant emissions, the project boundary will not be a considerable problem. In baseline-and-credit systems, however, indirect emissions, such as those from purchased energy, are typically also within the project boundary. This makes the decision more difficult.

Calculation of emission reduction and determination of emission intensities

The calculation of emission reduction requires information on the energy saved and its emission intensity. The procedures to determine the amount of energy saved are conventionally defined in ESCO projects.

Estimation of emission intensity requires among other things an analysis of dispatch order and fuels used. As they may change over time, the emission intensity may have to be modified respectively. The estimation of emission intensity is more difficult, if indirect emissions are relevant. The intensity should in many cases be calculated project-specifically. Particularly complicated would be the calculation of emission intensity in the case of indirect emissions from a district heating net-

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[1] *Cap-and-trade* -emissions trading refers to a system, where a cap is set for the emissions of each entity participating the scheme. The entities are entitled to trade emission allowances that they receive in an initial allocation with each other in order to reach their cap. In a *baseline-and-credit*-system, entities are rewarded with credits for specific activities to reduce emissions in comparison to a *baseline*, a scenario without the project.

work including several boilers and fuels or from combined heat and power production.

Possible revision procedure of the baseline
The baseline is determined based on several assumptions concerning e.g. fuel prices, technological development, and political and legislative changes. These may change significantly during the project lifetime. To allow a more informed estimation of the baseline, it can be revised if predefined changes occur. Revision is the more important, the more complex the energy system in which energy is saved and the longer the contract period in the ESCO project.

Monitoring procedure
The monitoring procedure of emission reductions must be defined in the planning phase of an ESCO project. In a cap-and trade system the monitoring can be arranged between the ESCO and its customer, since the regulator is not interested in emission reductions but emission allowances. In a baseline-and-credit system, however, monitoring of the emission reductions must be arranged according to the requirements of the regulator.

Monitoring of emission reductions
After the implementation phase of an ESCO project the energy saving indicators are monitored and energy savings calculated in a way decided by the ESCO and its client. If emission reductions were also included in the contract, some additional indicators would have to be monitored.

Possible validation, verification and reporting of emission reductions
In a baseline-and-credit system, emission reductions are crucial for the regulator, which may imply additional validation, verification and reporting requirements. This would obviously increase the costs of an ESCO project including emission reductions. In a cap-and-trade emissions trading system these steps would not be necessary.

4 GHG abatement potential with ESCOs in industry

The potential of ESCOs to reduce GHG emissions in the Finnish industry was explored in phases. First, the market potential of ESCOs in terms of savings in heat and electricity consumption per year was identified. Second, the emission intensities of electricity and heat on the average were estimated. The GHG abatement potential was obtained by multiplying the outputs of the two steps.

4.1 ESCO market potential

The market potential of ESCOs in Finland is part of the general economic energy saving potential. In this study, the market potential was estimated in the Finnish industry. The data was derived from two sources: annual reports related to the Voluntary Agreement on Energy Conservation and energy auditing information. The Finnish Ministry of Trade and Industry made the Voluntary Agreement on Energy Conservation with the Confederation of Finnish Industry and Employers in 1997. Companies that join the scheme will have to report their energy consumption, production, steps taken to improve energy efficiency, and the remaining energy efficiency potential annually. In the end of the year 2000, 91 companies representing 85% of the energy consumption in the Finnish industry had joined the scheme.

The Finnish Ministry of Trade and Industry has supported energy auditing since 1992. In total 747 industrial sites were audited during 1992–2000. Currently, a significant part of the audits is made in sites that have signed the energy saving contract.

The technical potential of ESCO projects is restricted by: i) monitoring opportunities of the energy efficiency improvement and ii) the reliability of the pre-feasibility data. The economic potential is restricted by the i) the estimation of energy savings obtained, ii) investment size and iii) the viability of the project.

In this study the market potential of ESCO projects was differentiated from the general energy saving potential by the following restrictions:

- the estimated pay-back time is 2–6 years. If the pay-back time is less than 2 years, companies are likely to make the investment by themselves. If the pay-back time is more than 6 years, the investment is seldom attractive for ESCOs.

Table 1. The market potential of ESCO-projects in the Finnish industry.

	Heat		Electricity	
	[GWh/a]	**[1 000 000 €/a]**	**[GWh/a]**	**[1 000 000 €/a]**
Energy saving potential	1 890	21	340	11
Investment potential [€]	200 000 000			

- the minimum investment is 50 000 €. If the investment size is smaller, the transaction costs from performance contracting may become excessively high compared to the investment.

It was estimated that the resulting investment potential was 200 million € (Table 1). The potential to save heat is remarkably larger than that of electricity.

The GHG abatement potential was derived from Table 1 and the emission intensities of energy saved. The emission intensities were estimated separately for electricity and heat.

4.2 Emission intensity of electricity

The *emission intensity of electricity* is not defined within the local context of a project, but within the whole electricity network. The emission intensity can broadly be estimated in two ways: based on *average* production or based on *marginal* production. In addition, demand-side projects should also take into account transmission and distribution (T&D) losses (Kartha et al. 2002), which on the average accounted for 3.5% in Finland in 2000 (Statistics Finland 2001).

In Finland, the average CO_2 emission intensity of electricity *generated* is fairly low in an international comparison: 160 g/kWh_e in 2000 (Finergy 2002). The average emission intensity in Finland of electricity *used* in the country taking into account the T&D loss was even lower as Finland is a net importer of power: 141 g/kWh in 2000.

However, the marginal emission intensity is higher due to the remarkable share of nuclear and hydro power production that are hardly affected by marginal changes in electricity demand. In the Nordic market it is also known that variable production costs of electricity in cogeneration (CHP) plants are lower than those of conventional condensing power plants. Further, electricity imports in Finland are mainly based on either the availability of competitive hydro power (imports from Norway and Sweden) or fixed contracts that are inelastic to price deviations (imports from Russia).

In this study, the marginal emission intensity was therefore estimated based on the production of conventional condensing power. During 1995–2000 around 80% of the fuels used in these power plants were GHG emission intensive coal and peat. Therefore the average emission intensity of condensing power in Finland has been 810 g/kWh_e during 1995–2000 with a standard deviation of only 3%.

4.3 Emission intensity of heat

The *emission intensity of heat* was estimated on an average basis, as the data available did not allow a site-specific, bottom-up analysis. The average intensity was explored from the Finnish Energy Statistics (Statistics Finland 2001). Black liquor, natural gas and wood fuels generate around 60% of energy in the Finnish industry (Figure 1). In cogeneration, which is widely used in Finland, the relative share of wood-based fuels and natural gas is even higher: around 80%. Cuts in heat consumption thus often reduce low emission electricity generation that must be replaced by emission-intensive marginal power plants, i.e. condensing power. This effect significantly reduces the emission cuts that are achieved through heat savings in the Finnish industry.

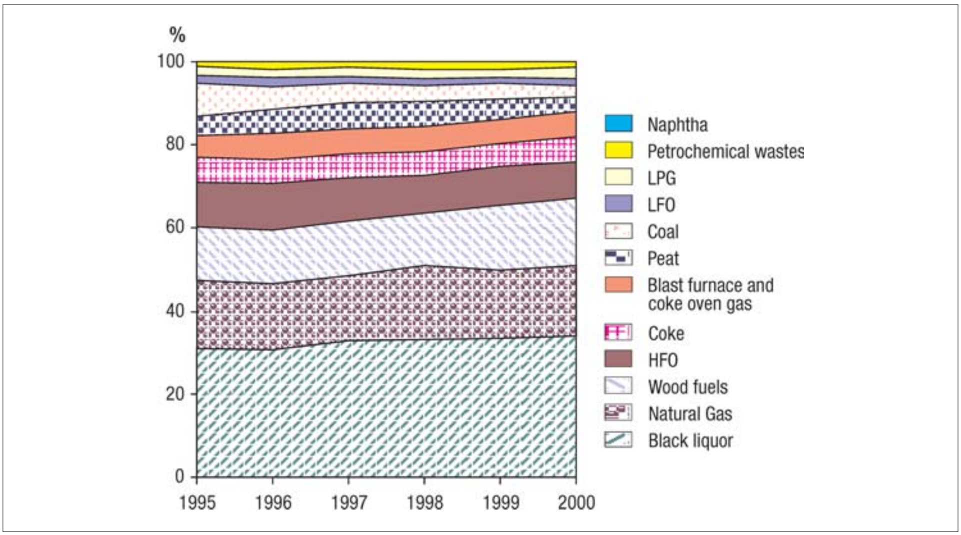

Figure 1. Fuel consumption in the Finnish industry 1995–2000 (Statistics Finland 2001).

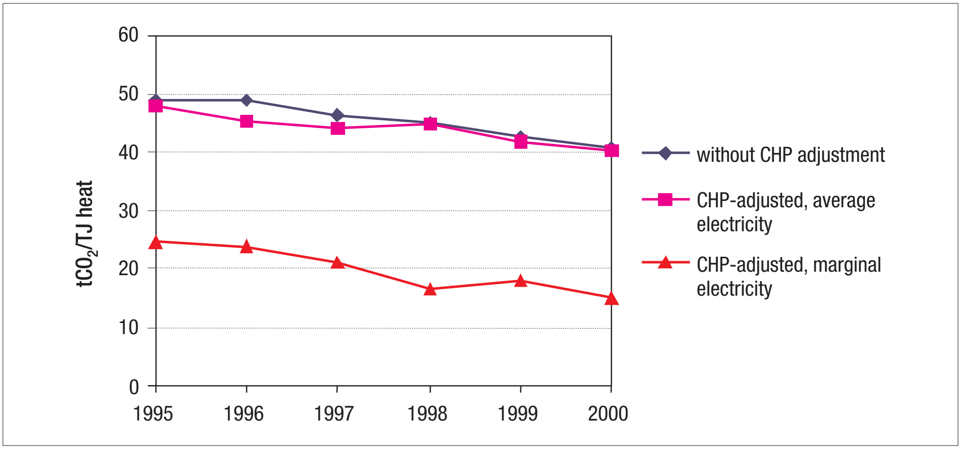

Figure 2. Development of emission intensity for heat in the Finnish industry 1995–2000.

The effect is illustrated in Figure 2. The CHP-adjusted emission intensity of heat is much lower than the unadjusted rate, when the adjustment is made using the marginal emission intensity for electricity. In 2000, the CHP-adjusted emission intensity of heat was 40 tCO_2/TJ with average electricity and 15 tCO_2/TJ with marginal electricity. Emission intensities for heat vary significantly across industries. For example, pulp and paper industry benefits from a high proportion of wood-based fuels and cogeneration.

4.4 Results

The GHG abatement potential of ESCOs in the Finnish industry is estimated at 0.3–0.4 Mt CO_2. This is around 8–13% of the total GHG abatement potential through energy efficiency improvement in Finland, which has been estimated at 3–4 Mt CO_2 (MTI 2001).

Table 2. Estimated GHG abatement potential of ESCOs in the Finnish industry.

	Market potential	**Emission intensity**		**GHG abatement potential**	
		Electricity, average	**Electricity, marginal**	**Electricity, average**	**Electricity, marginal**
	GWh	**tCO_2/GWh**	**tCO_2/GWh**	**tCO_2**	**tCO_2**
Electricity	340	141	843	50 000	290 000
Heat	1890	144	54	270 000	100 000
TOTAL				**320 000**	**390 000**

5 Discussion

The results of the project show that industrial ESCO projects in Finland to cut the consumption of electricity and those to cut the consumption of heat are in a very different position, when it comes to GHG abatement. Any conclusions on the GHG abatement potential depend decisively on the approach to the emission intensity of electricity. If the marginal approach is used as suggested here, some projects to cut heat consumption may even increase GHG emissions in Finland.

The results presented here are not based on a bottom-up analysis. It has also been assumed that all heat demand cuts in association with CHP will reduce electricity production from CHP.

In the current regulatory environment in Finland, there is little incentive for the private sector to trade emission reductions. The regulatory environment may, however, change e.g. due to an international emissions trading scheme. Emission reductions do not seem to emerge as a driving force for most ESCO projects. However, they can generate some extra cash flow, if transaction costs remain at a reasonable level compared to benefits. In individual projects the impact of emission reductions may be significant.

In the following, some specific recommendations for authorities, industrial federations and companies are given for actions to support energy efficiency improvement in Finland.

6 Conclusions

6.1 Principles for determination of emission reductions

In order to quantify the emission reductions in ESCO projects, the most important additional activity would be the estimation of emission intensity, which is not always trivial. The aim should be to standardise the calculation procedures as far as possible. Standardisation is in many cases difficult, but could be done at least concerning (1) the project boundary, (2) determination of the emission intensity, and (3) updating the baseline. Heat saving projects in association with separate heat production, heat saving projects in CHP production and electricity saving projects need differing methods. It would be important to give guidance to the emission intensity of electricity in particular. Initially only carbon dioxide should be included in the analysis to keep the procedures simple enough.

6.2 Extension of the “ESCO-concept” to cover GHG emissions

In Finland the “ESCO-concept” should be further developed so that it would take into account potential changes in the regulatory framework concerning greenhouse gas emissions. Emission reductions seem to become only a complementary incentive for ESCO activities, while benefits from the savings in energy costs remain the primary incentive. Therefore, the additional transaction costs of including emission reductions into the ESCO concept should be kept low. This would support in particular small ESCO projects.

6.3 Training and dissemination activities

In the ESCO business, a general problem has been the novelty of the business idea. Although clear benefits are offered, the customers may not be interested in ESCO projects since they are not familiar with the business logic. The same problem would probably exist in case of an emissions trading system. If an emissions trading system were introduced, a number of training and information services would be offered by industrial federations, educational organisations, consultancy companies etc. However, also public training and information dissemination among the potential ESCO customers would be needed, especially in the initial phase of the system.

6.4 Development of skills and strategy

Both ESCOs and their customers should acquire the needed skills to deal with emission reductions. They should be prepared for possible changes in the regulatory framework of ESCO projects and select a strategy to handle emission reductions in ESCO contracts.

6.5 Development of company procurement policies

ESCO projects have sometimes faced problems with the procurement policies of companies. These have in some cases complicated energy performance contracts. The potential customers should be made aware of the issue and, when necessary, review their procurement procedures (included *e.g.* in quality and environmental management systems). Authorities and industrial federations should address procurement policies in their information dissemination and training activities.

6.6 Guidance for the determination of CO_2-intensity of heat

Heat producers could be encouraged to improve their environmental reporting to include GHG emission intensities. For example in the case of district heating, the customers would be more capable of estimating the emission intensity of the saved heat, if different producers reported their emission intensities in a given format for certain periods. This reporting, however, should be developed in cooperation with the authorities and industry federations.

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Development Scenarios of High-Efficiency Power Plant Technologies in Centralised Electricity and Heat Production and their Impacts on Greenhouse Gas Emissions

Korkean hyötysuhteen voimalaitostekniikoiden kehitysnäkymät ja vaikutukset kasvihuonekaasupäästöihin

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Abstract

In the co-project of Fortum Engineering Ltd and VTT, new centralised fossil and renewable energy technologies and their development scenarios were studied. Also, the effect of these new technologies on the greenhouse gas emissions and the applicability of the new technologies into the Finnish energy system were considered.

In this technical report, both the study prepared by Fortum and the study prepared by VTT have been considered. Power plant technologies studied by Fortum are coal, natural gas combined and motor power plants. Also, the development scenarios of process industry and CHP technologies have been described by Fortum. VTT's study dealt with advanced combustion and gasification technologies, co-production of energy, fuels and chemicals, and high-temperature fuel cells and hybrid fuel cell systems.

The studied coal power plant technologies are so called ultra super critical (USC) plants, which have very high steam values. USC plants have been utilised for 40 years, but they have not yet played a substantial role in power generation. Currently, new materials and the need to cut the greenhouse gas emissions have increased the interest in USC plants. The main challenges in the development of the USC plants are in the material technologies. Also, water chemistry, construction technology and innovative planning are important in the development of the USC plants.

Natural gas combined power plants are commonly utilised in the combined heat and power (CHP) production. Combined technology is effective, has quite low investment costs and is fast to construct. The gas turbine processes are typically fuel-efficient and have low specific emissions. The development of materials and cooling technologies has made the high efficiencies possible.

Motor power plants have been developed from the ship engines. Motor power plants are already commonly used power technology. Still, the efficiency of the motor power plants will be increased by developing the motor process and by adding the combined cycle into the process.

In the process industry, the difference between the power-to-heat ratio of CHP generation and the energy use of the process creates both technical and commercial development potential in the power generation. The commercial potential has not earlier been utilised, when the planning basis has been only the energy demand of the process. The power generation has been rarely developed and optimised as a separate business activity in the process industry. New ideas, optimal utilisation of technology and the new planning methods make it possible to increase the power generation in the process industry, which is very attractive, because of the high efficiency of the CHP generation.

The potential and the market outlook of pressurised fluidised-bed combustion have declined, i.a., due to the good competitivity of natural gas combined-cycle technology, tightening emission standards, and the development outlook for gasifica-

tion combined-cycle technology. Development of a combined-cycle power plant process based on pressurised pulverised combustion of coal is still at an initial stage. The oxygen based IGCC plants in the world have so far been demonstration plants. The IGCC technology is expected to find commercial implementation first in residual oil gasification applications integrated to oil refineries and then in coal powered condensed power plants. In addition, one biomass-based IGCC plant has been constructed. This process is so called simplified IGCC, utilising pressurised air blown gasification and hot gas cleaning. The test trials of this plant were completed in 1999. The process is technically feasible also for large-scale demonstration. Gasification technology has also been developed for black liquor. The ChemRec black liquor gasification process is technically the most advanced process at the moment. The atmospheric process has been demonstrated and the pressurised process demonstration is about to start in Sweden and in USA. In utilising biomass fuels or black liquor, the IGCC process offers the possibility to significantly increase the ratio of electrical power to thermal power with combined cycle.

Catalytic combustion is expected to be commercialised first in small natural gas fuelled gas turbines and gasoline-fuelled microturbines. Catalytic combustion can also offer an alternative for the elimination of fuel-bound NO_x in the combustion of biomass gasification gas.

Gasification gas or pyrolysis oil produced from solid fuels can also be used in engine power plants. Obstacles to commercialisation in small power plant applications have been due to technical problems, especially those related to gas cleaning and oil quality.

Synthesis gas produced by gasification technology can be used for producing different gaseous or liquid fuels and chemicals and for energy production. In a flexible use of feedstocks and products, this co-production method offers a significantly more feasible alternative to present energy production plants. However, there is rather little experience available from large-scale production of biomass products, based on oxygen gasification. In Finland wood-processing industries and also other process industries could be suitable sites for co-production.

High-temperature fuel cells and hybrid fuel cell systems will be available technologies in power and CHP production of 0.2–10 MW size range within the next ten years, while large scale fuel cell power plants will not be constructed until in the more remote future. The first gasification applications will probably employ molten carbonate fuel cells. These cells have already been tested with gasification gas. The operation temperature of these cells is also more suitable than that of the solid oxide cells.

Tiivistelmä

Fortum Engineering Oy:n ja VTT:n yhteisprojektissa selvitettiin fossiilisiin ja uusiutuviin polttoaineisiin perustuvan keskitetyn energiantuotannon uutta tekniikkaa ja kehitysnäkymiä. Samalla arvioitiin uuden tekniikan vaikutusta kasvihuonekaasupäästöihin ja sovellettavuutta Suomen energiantuotantoon.

Raportissa on on tarkasteltu sekä Fortumin että VTT työn osuutta. Fortumin selvityksen kohteena ovat olleet hiili-, maakaasukombi- ja moottorivoimalaitostekniikat. Lisäksi Fortumissa on tarkasteltu prosessiteollisuuden kehitysnäkymiä ja vaikutuksia CHP-tekniikkaan. VTT:n osuudessa on tarkasteltu kaasutus- ja polttotekniikoiden kehitysnäkymiä, korkealämpötilapolttokennoja ja hybridivoimalaitoksia sekä yhdistettyjä kemikaalien, polttoaineiden ja energiantuotannon konsepteja.

Hiilivoimalaitostekniikoista on tarkasteltu ns. USC-laitoksia (Ultra Super Critical) eli laitoksia, joiden höyrynarvot ovat hyvin korkeita. USC-laitoksia on ollut käytössä jo noin 40 vuotta, mutta aluksi näiden laitosten rooli energiantuotannosa jäi vähäiseksi. Uudet paremmat materiaalit ja tarve rajoittaa kasvihuonekaasupäästöjä ovat lisänneet mielenkiintoa USC-laitoksiin. USC-laitosten suurimmat haasteet ovat edelleen materiaalipuolella, mutta myös vesikemian hallinta, valmistustekniikka ja innovatiivinen suunnittelu ovat tärkeitä USC-laitosten kehittämisessä.

Maakaasukombitekniikka on yleistä erityisesti yhdistetyssä sähkön ja lämmöntuotannossa (CHP). Kombitekniikka on tehokas, investointikustannuksiltaan edullinen ja laitostyyppinä nopea rakentaa. Kaasuturbiiniprosessit ovat luonnostaan kyvykkäitä suhteellisen hyvään polttoainetalouteen ja alhaisiin päästöihin. Korkeiden hyötysuhteiden taustalla ovat materiaali- ja jäähdytystekniikan kehittyminen.

Moottorivoimalaitosten moottorit ovat alunperin laivamoottoreista kehitettyjä moottoreita. Moottorivoimalaitokset ovat maailmalla yleisesti käytössä olevaa voimalaitostekniikkaa. Moottorivoimalaitosten hyötysuhdetta voidaan edelleen nostaa sekä kehittämällä moottoriprosessia että kombikytkennällä.

Rakennusasteiden eriparisuus prosessiteollisuuden CHP-tuotannossa ja tehtaan kulutuksessa sisältää sekä teknisen että liiketoiminnallisen kehityspotetiaalin. Liiketoiminnallinen potentiaali on aiemmin jäänyt Suomessa hyödyntämättä, kun voimalaitoksen suunnitelun lähtökohtana on pidetty tehtaan omaa energiantarvetta. Tekninen kehityspotentiaali näkyy siinä, että voimalaitosta on harvoin kehitetty ja optimoitu integaattituotannon lisäksi itsenäisenä energialiiketoimintakokonaisuutena. Uudet ajattelumallit, teknologian optimaalinen hyödyntäminen ja uudet suunnittelumenetelmät mahdollistavat prosessiteollisuuden sähköntuotannon kasvattamisen, mikä on erityisen houkuttelevaa CHP-tuotannossa sen korkean hyötysuhteen vuoksi.

Paineistetun leijukerrospolton potentiaali ja markkinanäkymät ovat heikentyneet mm. perinteisen höyryvoimalaitoksen kehityksen, maakaasukombitekniikan hyvän kilpailukyvyn, kiristyneiden päästönormien sekä kaasutuskombitekniikan kehitysnäkymien myötä. Hiilen paineistettuun pölypolttoon perustuva kombivoimalaitosprosessin kehitys on vielä alkuvaiheessa. Toistaiseksi maailmalla rakennetut happikaasutukseen perustuvat IGCC-laitokset ovat olleet luonteeltaan demonstraatiolaitoksia. IGCC-tekniikan oletetaan kaupallistuvan ensin öljynjalostamoihin integroiduissa pohjaöljyn kaasutussovelluksissa ja sitten kivihiilikäyttöisissä lauhdevoimalaitoksissa. Ilmakaasutukseen perustuvalla, ns. yksinkertaistetulla kaasutuskombiprosessitekniikalla on toistaiseksi toteutettu vain yksi koelaitos. Teknisesti prosessi on valmis myös suuren kokoluokan demonstrointiin. Kehitteillä olevista mustalipeän kaasutusprosesseista teknisesti pisimmällä on Chemrec-prosessi. Ilmanpaineinen prosessi on demonstroitu ja paineistetun prosessin demonstrointi on käynnistymässä sekä Ruotsissa että Yhdysvalloissa.

Katalyyttisen polton odotetaan kaupallistuvan aluksi maakaasua käyttävissä pienissä kaasuturbiineissa ja bensiiniä käyttävissä mikroturbiineissa. Katalyyttinen poltto voi olla vaihtoehto myös biomassan kaasutuskaasun poltossa syntyvän polttoaineperäisen NO_x:n eliminoimisessa.

Moottorivoimalaitoksissa voidaan käyttää myös kiinteistä polttoaineista valmistettua kaasutuskaasua tai pyrolyysiöljyä. Tekniikan kaupallistumisen esteenä pienvoimalasovelluksissa ovat olleet tekniset ongelmat, erityisesti kaasun puhdistukseen ja öljyn laatuun liittyvät kysymykset.

Kaasutustekniikalla tuotettua synteesikaasua voidaan käyttää erilaisten kaasumaisten tai nestemäisten polttoaineiden ja kemikaalien valmistamiseen sekä energiantuotantoon. Hyödyntämällä lähtöaineiden ja tuotteiden joustavan käytön yhteistuotanto tarjoaa huomattavasti taloudellisemman vaihtoehdon nykyisiin, pelkkää energiaa tuottaviin laitoksiin verrattuna. Happikaasutukseen perustuvasta biojalosteiden tuotannosta on kuitenkin suuressa kokoluokassa vähän kokemuksia. Suomessa puunjalostusteollisuuden ohella myös muu prosessiteollisuus voisi olla sopiva sijoituspaikka yhteistuotannolle.

Korkealämpötilapolttokennot ja polttokennohybridit ovat 0,2–10 MW:n kokoluokan sähköntuotannossa ja yhdistetyssä sähkön ja lämmöntuotannossa käyttökelpoisia teknologioita jo kymmenen vuoden kuluessa. Suurten polttokennovoimaloiden toteuttamisen aika on kauempana tulevaisuudessa. Ensimmäiset kaasutuskaasusovellukset toteutettaneen sulakarbonaattikennoilla. Näillä on jo saatu kokemuksia kaasutuskaasun käytöstä. Kennojen toimintalämpötila on myös sopivampi nykyisiin kiinteäoksidikennoihin verrattuna.

1 Introduction

This project has been a co-project between Fortum Engineering Ltd and VTT. The object of the project has been to study the current situation and the future scenarios of the high efficiency power plant technologies. Also, the applicability of these technologies into the Finnish energy system has been considered. The focus of the study has been on the power plants larger than 1 MW. The technologies considered by Fortum have been:

- coal power plants
- natural gas combined cycle power plants
- motor power plants.

Also, the development scenarios of process industry and CHP technologies have been studied by Fortum. The technologies studied by VTT have been:

- advanced combustion and gasification technologies
- co-production of energy, fuels and chemicals
- high-temperature fuel cells and hybrid fuel cell systems.

The information has been acquired by literature reviews, attending conferences and through own projects. Also, contact networks have been utilised, together with direct connections to the power plant manufacturers. The information collected for the project included company visits to the Puertallano coal gasification power plant, to the fuel cell research in the MTU-Fridrichshafen and Jülich and to the Siemens-Westinghouse (fuel cells and gas turbines).

2 Coal power plant technology

The studied power plants are so called ultra super critical (USC) plants. This means that the steam values of the power plant are very high (pressure > ~250 bar, temperature > 560°C).

USC technology has been utilised for 40 years. In the beginning, the material problems caused a bad reputation on USC technology, and these plants have not yet been in a substantial role in power generation. The development of material technology and the need to cut the greenhouse gas emissions have increased the interest in USC technology.

The biggest challenges of the current generation of the USC plants are still in the material technology. Also, water chemistry, construction technology and innovative planning are important in the development of the USC technology.

There are several research projects all over the world developing USC technology. The leading country in the USC technology is Japan. In Japan, the development of USC materials began earlier than in other countries. In Europe, Denmark has constructed the newest USC plants.

2.1 European USC project

Fortum's study is mainly based on the European USC project (advanced PF power plant), which has been supported by EU, and about 40 companies are participating the project. The EU project is coordinated by Denmark. One goal of the EU project is to demonstrate a very high steam value plant in 2010. The efficiency of the plant will be about 50–55%.

The general goal of the project is also to sustain the role of the coal in the future. The overall performance (energetic, economic) of the plant will back up the image of the coal and create a more favourable political climate for coal use.

The chosen burning technology is pulverized coal burning. Also, the multi-fuel boilers were considered, but they were not included in the project. There are two plant sizes to be developed: 400 and 900 MW_e. The plant is so called base load condensation power plant, but also the combined heat and power plant option is under discussion. The size of the demonstration plant will be 400 MW_e.

In the USC plants, the conventional steam line construction would increase the cost share of the steam lines from 3% to 15% of total investment, because of the more expensive special materials. This has motivated many boiler constructors to develop the boiler layout by minimizing the length of the most

Table 1. Efficiency and cost estimates for USC technology in 2002, 2010 and 2030.

Technology	Size, MW_e	Net efficiency, %			Investment, € / kW_e		
		2002	2010	2030	2002	2010	2030
	400	44	50	56	1000	960	920
	900	44	50	56	900	840	790

critical steam lines. Also, the heat transfer of the boiler has been improved during the project.

New constructions for preheating of feed water have been tested during the project. A new cooling system of steam turbine and the division of the high-pressure turbine have also been innovations in the development of steam turbine plant.

The project includes also testing of new materials in laboratory conditions. In the beginning of 2002, new sub-projects for testing the materials in real conditions were started. These projects consist of planning and construction of components, and preparation of the test site. The panning of tests for all critical components has been started. All these sub-projects aim to reach the point of real condition tests three years before the construction of demonstration plant. New materials will make possible thinner walls, which implies better heat transfer. Also, expensive materials will be saved.

The investment costs of USC plants have been studied during the project. The study showed that the USC plant will be cost-effective, but the variation in the price estimations of coal increases the uncertainty of the cost study.

3 Natural gas combined cycle power plants

Combined cycle power plant is based on so-called combined cycle process, which in this case has been defined as a combined process of a gas turbine and a steam turbine. The combined cycle process could be used in a condensation power plant or in a CHP plant, and the number of gas turbines could be one or more. The combined process has become common especially in the natural gas fired CHP plants.

Compared with the conventional power plants, high efficiency and high power-to-heat ratio in CHP production are typical characteristics for combined cycle power plants. Also, power adjustment is easy and fast start-ups are possible in gas-combined plants. In separate power production, efficiencies of 50–54% have been achieved with gas combined cycle power plants. Currently, the highest efficiencies are even 55–60% in new combined cycle plants with large-scale gas turbines. In district heating CHP plants, typical power-to-heat ratios are 1–1.15. Gas combined technology has relatively low investment costs, and these plants are also fast to construct.

Development of gas turbines has been fast in recent decades. In many cases, gas turbine processes have higher power density, better fuel efficiency and lower specific emissions than competing power technologies. The development of cooling and material technology of turbine parts has been the key to the increased efficiency of gas turbine process.

A common view is that the development of combined cycle power plants will be continuous at least ten years. Some of the trends behind the development of gas combined cycle power plants are for example the goal to increase turbine inlet temperature, development of cooling technology, development of new materials, continuously improved simulation technology and expected commercial introduction of super critical steam values in combined cycle power plants. It has been estimated that an efficiency of 65% could be achieved by 2010 in the combined cycle plants equipped with large-scale gas turbines.

The specific investment cost of gas combined cycle plants decreases significantly as the size of the power plant increases. For the small-scale gas combined plants, the specific investment is currently about 800 €/kW, while the specific investment of the large power plants is about 300 €/kW. Therefore, the research and development of combined cycle plants will probably focus on large-scale plants in the future.

In Finland, the combined cycle technology has been used in industrial and district heating CHP plants. The number of undeveloped sufficiently large heat loads by the natural gas lines currently limits the construction of new combined cycle plants in Finland. On the other hand, refurbishment of old plants could be a way to increase the utilisation of combined cycle processes.

4 Motor power plants

Motor power plants have been developed from the ship engine technology. Motor power plants could be divided into two groups according to the technology: otto-cycle and diesel engines. Fuels used in the motors are liquid or gaseous.

Currently, the best net electrical efficiencies of the motor power plants are 45%. In the combined heat and power production, the net efficiency of 92% could be achieved in the motor power plants.

Optimisation of the burning process can be further developed in the motor processes. The increase of the combustion pressure improves the efficiency of the motor. On the other hand, the increase of the combustion pressure raises the price of the motor by increasing the need of more expensive materials.

The combined cycle process has not been included in the motor power plants, because the temperature of the flue gases is relatively low in the current motor power plants. By increasing the combustion temperature and decreasing the cooling of the motor the flue gas temperature could be raised to a level that enables the combined cycle process in the motor process. On the other hand, the increase of the combustion temperature leads typically to higher NO_x emissions, which also tends to increase the investment costs of the power plant.

Emission limits and higher availability requirements of customers have an influence on the introduction of new motor power plant technology. A simplified conclusion of the development process could be to find the balance between efficiency improvement, lower specific emissions and guaranteed availability of power plant.

The efficiency of the motor power plants could be increased 3–5% by developing the motor process, this increases the total efficiency to the level of 50%. By including the combined cycle process into the motor power plants, the efficiency level of 60% will be targeted during the current decade.

The specific investment cost of the motor power plants is 500–800 €/kW with the current construction of the motor power plants. The specific investment depends on the technology and the size of the plant. It has been estimated that the specific investment with the current constructions may decrease

Table 2. Estimated efficiency targets of motors in the power generation.

Technology	2002	2015	2030
Simple cycle (plain engine)	47–49%	53–55%	55–56%
Simple cycle engine with STID *)		58–60%	61–63%
Combined cycle	53%		
Combined cycle (hot combustion)		61–63%	63–65%

*) STID = Steam Direct Injection Diesel

in the near future. Another scenario is that the tendency to cut the specific emissions of the motor power plants will stabilise the costs on the current levels.

In Finland, only a minor share of the energy is produced in the motor power plants. Also in the future, it is not probable that motor power plants would have significance in centralised energy production. In small-scale decentralised combined heat and power production, the motors will be a competitive alternative to the boiler and gas turbine technologies.

5 Development scenarios of process industry and CHP technologies

Finland is one of the leading countries in relation to the population among the countries utilising the combined heat and power production. Advantage of the CHP production is high energy efficiency. The CHP process have been utilised both in district heating and in the process industry.

The difference between the power-to-heat ratio of the CHP plant and the demand of process creates an optimisation potential. Commercial development potential exists, when the power-to-heat ratio of the factory is lower than the optimal or maximal power-to-heat ratio of the CHP plant. This commercial potential has not been utilised in many cases, when the planning of the CHP plant has been purely based on the energy demand of the factory. Technical potential exists, because power generation has been rarely developed and optimised as a separate business unit.

It is possible to increase the power-to-heat ratio of the process industry by power plant engineering. The potential to increase the power generation in the CHP plants of process industry is 5–20%. Also, the current technology for storing the steam makes possible the higher power-to-heat ratios in the planning phase of the CHP plants. In the case of very wet fuels, the steam drying technology could increase the power production per dry matter content of fuel.

The development of process planning has made it possible to cut the heat demand of processes considerably. The bottleneck in the optimisation of large integrals has often been the division of the planning into different sectors without communication of each other. Also, the utilisation of wastes as an energy resource creates potential for the integration of processes.

The development of the drying process creates significant potential to cut the energy demand of the forest industry. The efficiency of the drying process could be increased by replacing indirect steam drying processes with technologies like infrared drying or airborne web drying. Also, drying tech-

Table 3. Estimates of power generation potential in process industry.

Technology	Potential	Demand of biomass (consumption ratio)	Investment, k€/kW	Transition period
Heat saving	10%	–1	0–1000	5 years
Biomass based condensation power	?%	3	1500	5 years
Exergy oprtimisation of steam demand	20%	1	0–1000	5–10 years
Power-to-heat ratio	5–10%	0–1	0–1000	5–10 years
Drying	10–15%	0	1000	5–10 years
Gasification	300%	1	2000	10–30 years

nologies avoiding the phase transition of water in the drying process have been developed, for example technologies utilising mechanical pressure or impulses of steam.

There are several technological methods to increase the power generation of process industry. Some of these methods are fast to implement, whereas some of the methods will require a longer period to be in common utilisation. Some of the technologies have almost zero investment costs (for example some energy saving methods). Anyway, many methods have quite similar specific investments as the conventional power capacity.

6 Efficiency and CO_2-emissions

In fossil fuel based power generation, the most important greenhouse gas is carbon dioxide. Specific CO_2-emissions of power generation could be reduced by improving the efficiency. CO_2-emissions of power generation as a function of efficiency have been presented in figure 1.

7 Advanced combustion and gasification

The potential and the market outlooks for pressurised fluidised bed combustion (PFBC) of the first generation have weakened. This trend is due to improvements in the efficiency of conventional steam power plants, increased use and good competitiveness of natural gas combined-cycle technology, more stringent emission standards that require a very efficient removal of sulphur and nitrogen oxides, and superior chances of gasification combined-cycle technology to meet the efficiency, emission and CO_2 removal targets set for future coal-fired power plants. In addition to fluidised bed combustion, a combined-cycle power plant process based on pressurised combustion of pulverised coal will also be developed. However, the development of this process is clearly at a more early stage than that of fluidised bed technology.

The IGCC plants constructed so far are based on oxygen gasification and are demonstration plants. IGCC technology is expected to be commercial-

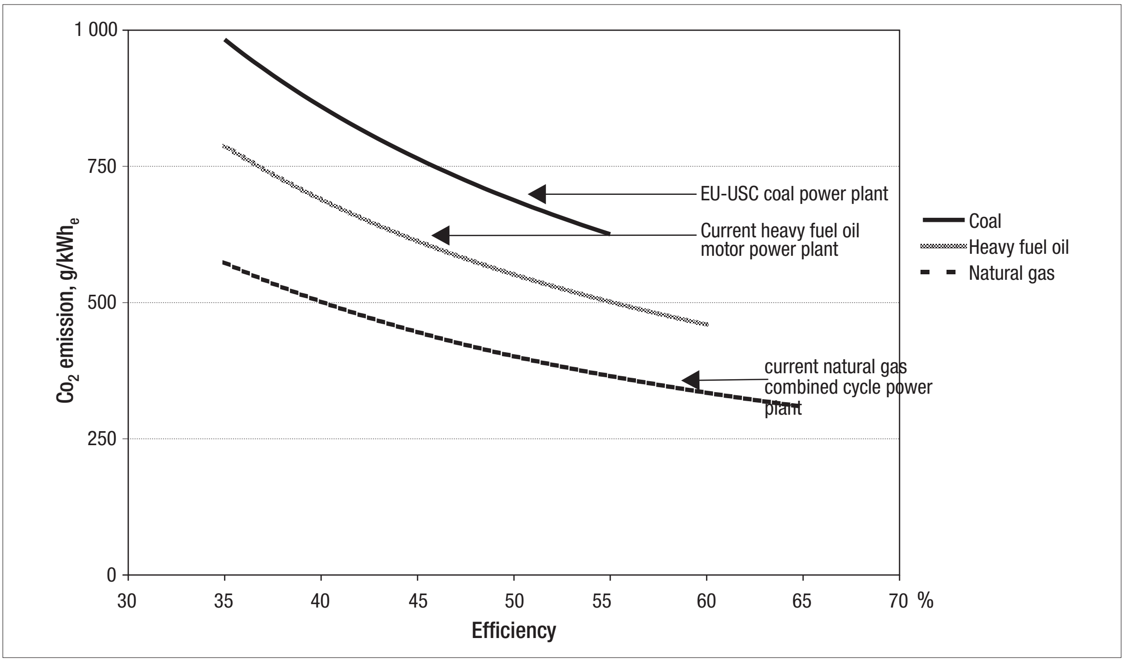

Figure 1. CO_2 emissions of power generation with different fuels and emission levels of some power technologies.

ised first in residual oil gasification applications integrated to oil refineries and then in coal-fired condensed power plants. The time schedule of commercialisation is primarily dependent on commercial competitiveness with conventional steam power plants and natural gas combined cycles. In Finland, the possible application of this technology may be limited to the construction of residual oil gasification plants to oil refineries. These plants could at least partly be constructed as combined power and process steam production plants.

In Finland, the work focused mainly on developing a so-called simplified gasification combined-cycle process (simplified IGCC), in which solid fuel (biomass, peat, coal) is gasified in a pressurised fluidised bed gasifier with the aid of air. So far, only one test plant based on this technology has been constructed. The plant is located at Värnamo, South-Sweden, and its test runs were completed in 1999. The process is technically ready for large-scale demonstration. However, the construction of the first plants would require an investment subsidy that exceeds the conventional one, and/or a significant improvement in the competitiveness of power produced from renewable fuels.

The ChemRec black liquor gasification process is technically the most advanced process at the moment. The atmospheric process has been demonstrated, though still suffering some difficult material problems. The pressurised process demonstration is about to start in Sweden and in USA. Successful black liquor gasification could offer an interesting alternative for traditional chemical recovery boiler. The gasification could significantly increase the ratio of electrical power to thermal power with combined cycle. Utilising black liquor and bark, the modern pulp mills are self-sufficient in energy production. However, as a whole the electricity used in paper and pulp industry is mainly imported.

The main benefits of catalytic combustion are in the stability and efficiency of combustion, the emissions of carbon monoxide, hydrocarbons and, in particular, thermal NO_x being very small. Thanks to the low NO_x emissions, the interest in applying catalytic combustion in power generation is increasing, in particular, in connection with the gas turbine process. Catalytic combustion has been assessed to be the best and most reasonable alternative, when the level of NO_x emissions shall be less than 5 ppm. The marketability of catalytic combustion technology may be verified during the next few years. It is expected that catalytic combustion will first be commercialised in natural gas fuelled small gas turbines of 1–5 MWe and in gasoline-fuelled microturbines (<100 kWe, hybrid vehicles).

One problem identified in the biomass-fuelled IGCC plant is due to nitrogen compounds in the gas, like ammonia, which forms NO_x in combustion. The removal of ammonia from gasification gas, i.a., catalytically prior to gas combustion is under intense research and development, i.a., at VTT. Another alternative of preventing the formation of ammonia-derived NO_x is catalytic combustion. This method enables the achievement of very low fuel-derived NO_x emissions. Simultaneously, emissions of CO and hydrocarbons as well as stability problems in the combustion of gas with a low calorific value can be eliminated. Catalytic combustion of volatile organic substances is of commercial technology, and some Finnish companies have gained know-how in this particular field.

Gasification gas or pyrolysis oil produced from solid fuels can also be used in engine power plants. Technical problems related, i.a., to gas cleaning and oil-grade issues have prevented the commercialisation of this technology in small power stations. In Finland, new catalytic gas cleaning technology has been under development during the recent years. This technology will enable the construction of gasification engine power stations in the size class of 0.5–3 MWe. The commercialisation of the process requires the construction of a demonstration plant, and long-term experience. Oil produced from wood or other biomass can be stored and transported for use in boilers or motor power stations. The technology is presently at an experimental stage and requires commercial-scale demonstration prior to its commercialisation. Figure 2 shows schematically the classification of different gasification processes.

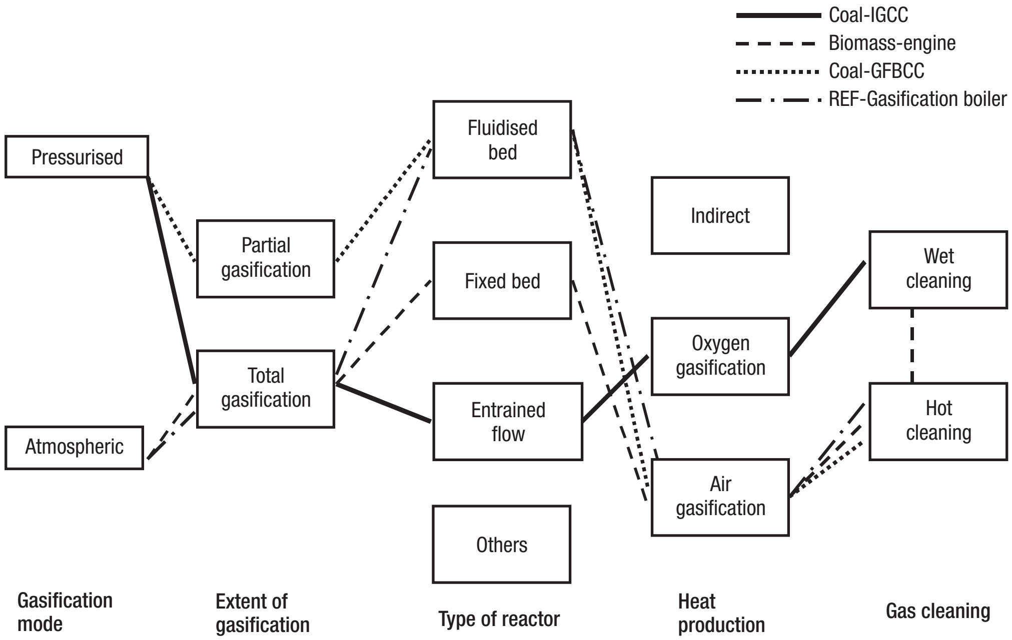

Figure 2. Classification of gasification processes.

8 Co-production plants

By employing gasification technology, different carbon-containing feedstocks, like carbon, inexpensive industrial wastes and by-products, and biomass and municipal waste, can be converted to clean synthesis gas consisting of hydrogen and carbon monoxide. The product, synthesis gas, can be used for producing different gaseous or liquid fuels, and chemicals, and for energy generation. The traditional market of gasification has been in the production of synthesis gas for the production of industrial chemicals. Gasification is also seizing new energy production markets, as a consequence of the development of gas turbines, liberated power production markets and more stringent environmental regulations. In co-production, the share of synthesis gas in energy generation or in the production of fuels and chemicals is dependent on the market demand. The aim is to maximise the utilisation of raw materials and the value of products. In this way, the capital invested in the plant is also used more effectively than in simple energy production. The flexible use of feedstocks and products offers a significantly more feasible alternative than the present plants that generate only energy. Figure 3 shows the gasification based co-production possibilities schematically.

In energy production, the integrated combined cycle power plant (IGCC) based on pressurised gasification can be employed. This process integrates gasification and gas cleaning to power generation in a gas and steam turbine. IGCC is one of the most efficient and cleanest power generation methods (like natural gas combined-cycle power plant) available for many alternative feedstocks of gasification. Both the IGCC technology and the conversion of the synthesis gas product to liquid products have been demonstrated successfully, i.a., in research programmes of the U.S. Department of Energy. The aim of the co-generation projects is to convert synthesis gas generated from various raw materials to fuels and chemicals. With the Fischer-Tropsch technology, fuel liquids are produced for replacing gasoline and diesel fuels. The methanation processes of synthesis gas aim at producing a versatile industrial chemical, methanol. If the on-going projects indicate that the process concepts are both technically and economically feasible, the construction and implementation of new co-production plants may be started. As a conse-

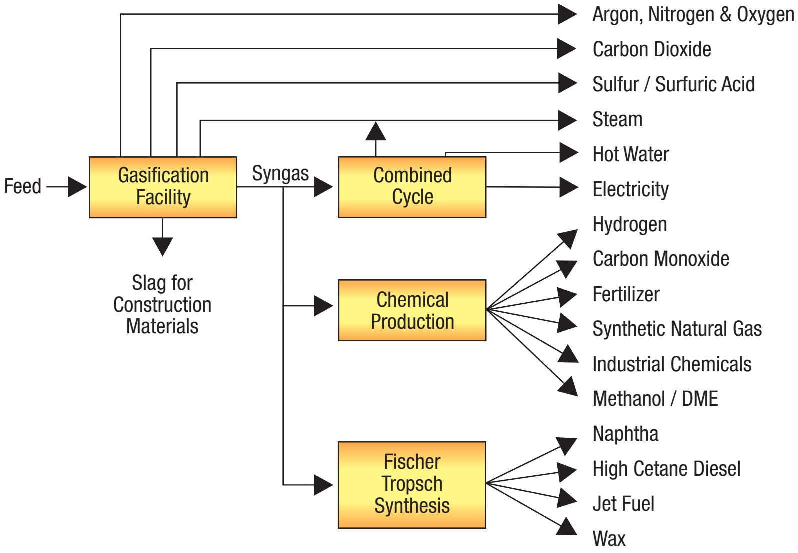

Figure 3. Gasification co-products-enhancing economics (Rao 2001).

quence, greenhouse gas emissions, in particular carbon dioxide ones, may be reduced efficiently.

In Finland, the co-production plants of liquid fuels and chemicals could be based on biomass resources. However, there is rather little experience from the large-scale production of bio-products based on oxygen gasification. Development work has been done primarily in conjunction with the development of IGCC technology. It looks like there would be sites for a large alcohol production plant only in connection with large pulp mills. The production costs would be clearly higher than the present prices of gasoline and methanol produced from raw oil and natural gas. Consequently, additional basis for the use of biofuels should be found, i.a., from emissions to the environment. Co-production plants could be sited at wood-processing plants and also in other process industries.

9 Fuel cells and hybrids

In energy production, high-temperature fuel cells and fuel cell hybrids will be available technologies in the size class of 0.2–10 MW power production and combined power and heat production within the next 10 years. The time of large fuel cell power plants will become in a more remote future. As regards commercialisation, the German-American Siemens Westinghouse, American Fuel Cell Energy and its German partner MTU Friedrichshafen, and a number of Japanese well-known energy companies are already well under way. There are also a high number of other developers of smaller size classes in the world. All significant fuel cell developers will first launch natural gas fuelled products to the market. These technologies offer higher efficiencies of power production and smaller emissions than the present or developing competing technologies, i.a., combustion engines and turbines. Specified markets are primary short-term targets of the fuel cell manufacturers. As a consequence of public energy programmes that favour environmentally friendly energy production methods, the marketability of fuel cell technologies may improve. Research and development of high-temperature cells and fuel cell hybrids should be focused on reducing the price of fuel cell modules and systems and on improving the power density of the cells. Figure 4 shows the estimated performance of power production systems.

In Finland, research and development of high-temperature cells is increasing as a consequence of intensive commercialisation efforts of foreign cell developers and of increasing interest of Finnish in-

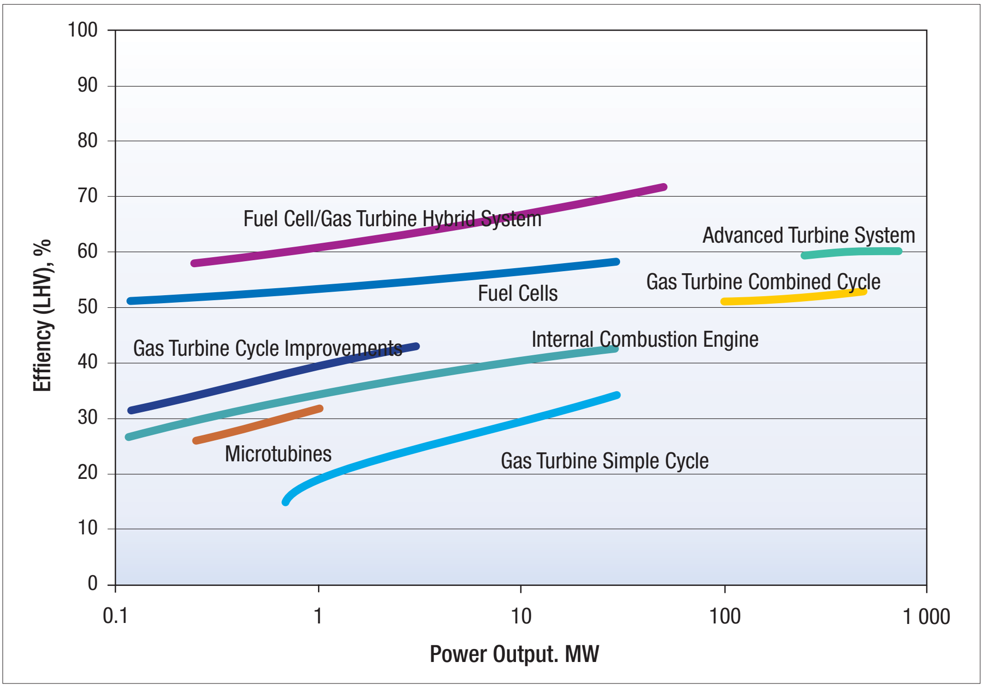

Figure 4. Estimated performance of power generation systems (HFC 2001).

dustries, like Wärtsilä, and of the National Development Agency of Finland and VTT. As research and development of high-temperature cells has been carried on for a long time in other countries, it may be feasible first to acquire know-how to Finland, to co-operate with foreign institutions and to develop technologies for Finland's specific conditions.

In Finland, the gasification technology of biomass and wastes for energy production has been developed intensively. A longer-term alternative of particular interest to Finland is the use of gas from the gasification of biomass and different wastes, and maybe also pyrolysis oil, also in high-temperature fuel cells and fuel cell hybrids. The development of optimal gasification technology for fuel cells and the cleaning of gasification gas for fuel cell use would be one specific object of research and development. Efficient operation of the fuel cells requires a suitable H_2/CO ratio of the product gas and a very high purity regarding, i.a., sulphur compounds. The present target of gas cleaning is the use in turbines and engines. According to studies performed, the solid oxide fuel cell is a more efficient component of the gasification combined cycle process, i.a., with regard to electric power. However, molten carbonate cells may be used in the first applications of gasification gas. Experiments from the use of gasification gas in these cells and the suitability of cell operation temperature are in favour of the use of molten carbonate cells. There is so far no well-operating and economical cell stack available.

10 Efficiency and cost estimates

Development of electrical efficiency and investment costs of different technologies reviewed are assessed in Table 4. The values are only indicative and do not consider, e.g., the effect of size class.

Table 4. Efficiency and cost estimates for new power production technologies.

Technology (fuel)	Size class MW	Efficiency (%) Year 2002	2010	2030	Investment cost ($) /$\text{kW}_e$ Year 2002	2010	2030
PFBC (coal)	50–300	45	50	55	1 250	850	800
IGCC (coal/oil)	300–1 000	51	55	57	1 200	1 000	850
IGCC (biomass)	30–150	47	50	53	1 900	1 500	1 200
IGCC (black liquor)	100–400	30	35	38	1 700	1 500	1 200
Gasification (biomass etc.) engine	0.5–10	35	36	38	2 000	1 800	1 500
MCFC (CH_4, etc.)	0.2–50	47	55	58	8 000	1 500	1 000
SOFC (CH_4, etc.)	0.2–50	45	55	63	10 000	1 500	700
Hybrid FC/GT (CH_4, etc.) etc.)	0.3–70	58	70	75	>10 000	1 000	600
Gasification (biomass etc.) -FC	0.5–10		45	50		?	2 000
IGFC (coal)	300–1 000		60	62		?	
IGFC (biomass etc.)	30–150			55		?	

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The Impact of IT on Greenhouse Gas Emissions in the Forest Cluster

IT:n mahdollisuudet metsäklusterin kasvihuonekaasupäästöjen vähentämisessä

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Abstract

Introduction of new technologies to business and production processes has direct and indirect impacts on greenhouse gas emissions and, hence, on climate change. GHG impacts of, e.g., e-commerce have been studied previously (Romm et.al 1999), but the forest cluster has attracted limited attention. This article is based on the Jaakko Pöyry Consulting study Eclogue that was part of the Climtech technology program of National Technology Agency (Finland). The study focused on technologies that originate outside the forest cluster and that have not yet been widely applied in it, such as e-commerce, smart packaging and wireless technologies.The research approach is based on three major components: a technology matrix, a hot spot analysis and a GHG impact assessment. The technology matrix contains a set of prominent technologies/concepts commercially available or about to be commercialised. The hot spot analysis links the technologies/concepts to value chains of representative products of the forest cluster. The GHG assessment is a qualitative assessment of possibilities to reduce GHG emission in a forest cluster. As technologies complement each other, three groups have been formed. Firstly, technologies that can improve production processes in the forest cluster, e.g. data mining, are considered. Then, technologies that support new business models, e.g. e-commerce and collaborative commerce, are studied, and finally, technologies that are part of the complementary relationship of electronic media and paper, e.g. e-paper.

Changes in energy consumption and potential improvements in energy efficiency dominate the impact on GHG emissions. The forest industry cluster (forestry, mechanical wood, pulp and paper, printing and publishing, related and supporting industries) is a large and multi-dimensional field. Most industries within the cluster are very capital intensive. Hence, the cluster industries have traditionally been hesitant to adopt new technology. This study identifies opportunities for the sector to move ahead and take advantage of new tools. When seeking key technologies that would determine the scenarios of impact, information emerged as the one common factor. Information (and its proper management) seems to be the one true pivot around which the possibilities to reduce GHG emissions in the forest cluster revolve.

Tiivistelmä

Uusien teknologioiden käytöllä tuotantoprosesseissa ja liiketoiminnassa on suoria ja epäsuoria vaikutuksia kasvihuonekaasupäästöihin (KHK-päästöihin) ja sitä kautta ilmastonmuutokseen. Esimerkiksi sähköisen kaupankäynnin vaikutuksia kasvihuonekaasupäästöihin on tutkittu (Romm et. al 1999), mutta sen yhteys metsäklusteriin on jäänyt toistaiseksi lähes huomiotta. Tässä tutkimuksessa keskitytään teknologioihin, jotka on kehitetty metsäklusterin ulkopuolella. Valittuun teknologiajoukkoon kuuluvat mm. sähköinen kauppa, älypakkaukset ja langattomat ratkaisut.

Tutkimus kiteytyy kolmeen pääosioon: teknologiamatriisiin, vaikutusten kohdentamiseen (hot spot -analyysi) ja KHK-vaikutusten arviointiin. Teknologiamatriisi sisältää lupaavia teknologioita/toimintatapoja, jotka ovat joko kaupallistettuja tai parhaillaan lähestymässä kaupallistusta. Kullekin teknologialle on esitetty arvio laajamittaisen käytön todennäköisyydestä sekä vaikutuksesta metsäklusterin KHK-päästöihin. Tarkasteluajanjakso ulottuu vuoteen 2030. Hot spot -analyysi yhdistää tutkittuja teknologioita metsäklusterista valittujen edustavien tuotteiden arvoketjuihin. Kasvihuonekaasujen vähennysmahdollisuuksia metsäklusterissa arvioidaan kvalitatiivisesti. Tarkas-

teltavat teknologiamuuttujat voidaan jakaa kolmeen teknologiaryhmään.Ensimmäiseen ryhmään kuuluvat tuotantoprosesseja hyödyttävät teknologiat, esim. tiedonlouhinta. Toiseen ryhmään kuuluvat uusia liiketoimintamalleja tukevat teknologiat, esim. sähköinen kauppa. Kolmantena ryhmänä ovat teknologiat, jotka liittyvät paperin ja sähköisen median rinnakkaiseloon, esim. sähköinen paperi.

Vaikutukset kasvihuonekaasupäästöihin muodostuvat lähinnä energian kulutuksessa tapahtuvista muutoksista. Metsäklusteri on laaja ja moniulotteinen toimintakenttä. Useimmat klusterin teollisuudenalat ovat varsin pääomavaltaisia ja ovat siksi perinteisesti olleet hitaita uuden teknologian käyttöönotossa. Tässä tutkimuksessa tunnistettiin muutamia mahdollisuuksia hyödyntää uusia teknologisia ratkaisuja ja liiketoimintamalleja. Informaatio (ja sen tarkoituksenmukainen hallinta) näyttäisikin olevan ratkaiseva tekijä, jonka ympärille kiertyvät metsäklusterin mahdollisuudet käyttää uusia teknologioita kasvihuonekaasupäästöjen vähentämiseen.

1 Introduction

This article describes the results of a project called ”The impact of information technology on the reduction of greenhouse gas emissions in the forest cluster”. The codename ECLOGUE has a connection to the e-Cluster and the GHGs. In the research project, information technology was defined broadly to include various technologies that utilise computer technology, support its development or create new modes of behaviour and business practices. Internet technologies, e-commerce, smart packaging and wireless technologies were among the topics included in the study. Internet technologies contain a wide group of solutions related to e.g. networking and knowledge management. The forest cluster includes forestry, pulp and paper, mechanical wood processing, wood furniture manufacturing, printing and publishing as well as other related and supporting industries and specialty input providers (suppliers of key products to the industry).

The aim was to investigate the future impact of new technologies that come from outside the traditional forest cluster. Many of these technologies are what one might call “enabling”, i.e. they potentially accelerate development in widely disparate areas. The Climtech program looks beyond the time frame of the Kyoto protocol, up to the year 2030. The pace of development over the past 30 years has been overwhelming in the forest cluster and, most of all, in the ICT industries. The climate change triggered by greenhouse gas emissions is a slow and partly unpredictable process. Markets and businesses have been globalising at a breakneck speed over the past few decades. Against this background, one realises the immensity of the task of evaluating technologies and impacts so far ahead in the future. The choice made is to report technologies up to a certain point in late 2001 and humbly acknowledge how quickly individual technologies may fade or never even come to bloom. However, general trends, hopefully, fare better – and technologies here should be taken to represent those general trends.

The article consists of three major chapters. The first (Chapter 2) is about the identification and introduction of a group of selected new or emerging technologies. The second (Chapter 3) gives an illustration of product value chains in the forest industry cluster. The third (Chapter 4) is about the potential impact of technologies assessing the impact of groups of technologies (three scenarios) on greenhouse gas emissions in the forest industry cluster. The assessment is qualitative with the direction of impacts provided. It should be pointed out that this analysis is confined to one sole industrial cluster, and the overall impact of the technologies (including production and disposal in other clusters) may be quite different.

The evaluation of technologies is confined to industrialised countries where high technology is presently available. We, again, acknowledge that this group of countries is likely to expand during the period of analysis up to 2030. Structural changes in the world economy and global distribution of wealth are, however, beyond our scope. This fact is important especially when the breakthrough of technologies is estimated. In developing countries, basic infrastructure and technology is lacking to such an extent as to hinder adoption of ICT technologies. The situation in developing countries is also different in terms of cost-efficient GHG abatement, with many more opportunities to reduce industry emissions using conventional technology – also in the forest cluster.

Thus, what follows is *an assessment of the impact of* ***a certain set of representative technologies****, visible today on* ***a certain industry*** *cluster, as it is today* ***based on a set of assumptions that seem reasonable today****.*

Given these warnings, the reader may enter the analysis.

2 Technologies

The technology matrix, the hot spot analysis and the GHG impact evaluation form the core of the methodology used in this section. A certain technology is in the public (and sometimes scientific and commercial) eye often connected only to its original field of application. Our approach is to seek new application opportunities boldly in expected and unexpected directions. The solution to multi-dimensional problems requires the use of multi-dimensional approaches. The technology matrix and related Kyoto staircase are introduced in this chapter. Hot spot analysis and GHG impact scenarios are explained in chapters 3 and 4 accordingly.

This chapter is divided into the introduction of technologies and the placement of them into the so-called technology matrix. The technologies have been divided into three categories 1) Paper, electronic media and intelligence, 2) Efficient ICT systems, and 3) New commercial practices. The latter part includes also the display of technologies in the Kyoto staircase.

2.1 Three groups of technologies

Paper, electronic media and intelligence

Electronic ink and electronic paper A family of technologies modifying or imitating the conventional paper interface known as the printed page. Electronic ink is a proprietary material that is processed into a film for integration into electronic displays. Electronic paper is based on printable plastic electronics. The print can be created with two methods: using print colours that react electrically or using a print surface that reacts electrically.

Identification chips A family of technologies providing items with traceable identity. Radio frequency identification (RFID) technology has allowed the self-adhesive label to become a mini-version of the computer. Labels can have data storage, built-in security features and integrated chips which enable product manufacturers to read and write data to the tags and to retrieve the data at any later point in time. A Japanese company has developed a silicon chip for security applications so small that it can even be embedded in money. This new chip is expected to enjoy much higher demand than conventional ID chips, which are significantly larger in size.

Mobile imaging A family of technologies extending the forms and norms of communication. Mobile imaging is a service, which is devised to back up multimedia messaging services (MMS) and wireless printing. MMS is a new, versatile messaging service that can carry multimedia contents, including photographs, video clips, sound bites, text, maps, graphs, layouts, ground plans, cartoons, animations etc. The user can send the photograph to another multimedia handset or to a Web service, where it can be viewed, printed or stored.

Smart clothing A family of technologies making your clothes active. This concept is based on a permanent integration of clothing and technology. For example, the censor technology monitoring the wearer and his surroundings can be permanently embedded in the clothing. The user interface can be e.g. a piece of textile, a watch, eyeglasses or some mobile device.

Smart packaging A family of technologies to intelligently encapsulate and safeguard goods in transit. Intelligent packages can for example interact with the environment. A package containing a sensor can show the product temperature or record the storage conditions of an item.

Efficient ICT systems

Data mining A family of technologies processing data to knowledge. Data mining is simply about using computer technology to extract actual information from mere facts. One example of technologies for data mining is the self-organising maps (SOM), invented by the Finnish professor and Academician Teuvo Kohonen in the early 1980's. SOM is what is known as an "unsupervised" neural network. This means that the network does not need any direct guidance from the user in its basic operation: it simply takes a mass of data and analyses it. However, the interpretation of results has to be made by the user, though various pieces of intelligence are being built into and around the SOM.

Mobile remote control A family of technologies extending the reach of process control. Mobile remote control means that operators can control a process by using their mobile devices. In forest industry an example could be, for example, one where a paper machine gives a signal of problems occurring and an alarm including a message is directed to the relevant personnel's mobile phones. Whether operators can change process parameters from the mobile phone directly or have to do the same thing manually at the paper machine controls depends on the application.

Nanotubes A family of technologies built around the production and use of a new material. Today, chipmakers are constantly battling to make the channel length in transistors smaller and smaller – the channel being the path where data travels from one place to another inside the chips. A carbon nanotube, i.e. a sheet of graphite rolled into a tube measuring up to several dozen nanometers in diameter and around 1 micrometer in length, comes in a variety of shapes and sizes and exhibits differences in such properties as strength and conductivity. Small variations in such factors as materials, temperature and pressure of the manufacturing process can yield final products with a quite different set of characteristics.

New computer circuits A family of competing technologies aiming to increase computing power. At the moment, one might distinguish between three schools of thought in developing computer circuits. One thinks there is a lot left to extract from silicone. Another concentrates on optical circuits (the velocity of light being the key advantage). A third puts its faith in nanocircuits (size and materials being the main topics). Combinations of these are also already visible, e.g. in hybrids of optical and silicon circuits.

Organic light emitting diode (OLED) displays An example from a family of technologies built to produce thin, foldable, energy saving displays. OLEDs, taken, as examples of the family of new display technologies, are thin films that consist of stable organic materials. The materials emit light when an electric current is applied to them. The amount of light depends on the voltage. They differ from the currently widely used liquid crystal displays (LCDs) by this light emitting property that removes the need for a separate source of backlight.

Portable fuel cells A family of technologies built around energy production from electrochemical devices. A fuel cell produces electric power from either hydrogen or alternative fuels such as methanol, propane, butane or natural gas. The waste products produced by a fuel cell are water, carbon dioxide and heat. Recently, most of the fuel cell companies have focused their methanol fuel cell research on hybrids, a combination of batteries and fuel cells as backup; mostly in "sub watt" categories such as mobile phones and lights that fit in a pocket.

Wireless printing A family of technologies built around wireless capacity and smart printers. Wireless printing requires the use of "a common language", that is, a wireless communications standard. Currently the three competing standards are Bluetooth, IR (infra red) and WLAN (802.11b). Tuned to a shared standard and using communication chips, two devices can communicate, e.g. a laptop computer and a wireless printer. The handheld device and the printer communicate together using pre-defined formats because of the limited memory and computing capabilities of current handheld devices. The content to be printed can be anything either stored on the device or "pointed at" by the device (i.e. an Internet address).

New commercial practices

Collaborative commerce/P2P A family of technology-enabled business practices built around networked collaboration. The arrival of business-to-business exchanges on the Web has created new ways for business partners to work together. Even after the end of the first, crazed era of the dot-com, corporate strategists and venture capitalists are embracing collaborative commerce as the next generation of e-commerce and an evolution of the traditional supply chain process. By using Web servers as hubs for collaborative commerce efforts, companies are seeking to exchange proprietary data, jointly manage projects and cooperate on the design of new products.

E-commerce (B2B, B2C) A family of technology-enabled business practices built around on-line commerce. E-commerce can be defined as conducting business on-line. Business can be transacted between two firms (B2B) or between a firm and a consumer (B2C). Conducting business on-line includes, for example, buying and selling products with digital cash and via Electronic Data Interchange (EDI).

Print-on-demand A family of technology-enabled business practices built around producing paper copies of digital content. The business model of print-on-demand is based on printing digital copies of publications when demanded by the customer. This form of delivering content makes it possible to deliver print runs of just one, thus it personalises service, books no longer have to run out of print and the problem of excess copies in storage is solved as well.

2.2 Technology matrix and Kyoto staircase

The technology matrix contains promising, innovative technologies and ways of working. The two dimensions of the matrix are the probability that the specified technology or commercial practice makes a wide-scale breakthrough on the market, and its potential impact on greenhouse gas emissions in the forest cluster. The matrix is intended to provide a starting point for the evaluation of technologies. The technologies used in the evaluation are often interrelated; “families of technologies”, dependent on the type of use, connected in various

Probability of general breakthrough			
Large	– e-commerce (B2C) – smart packaging	– Nanotubes – wireless printing – new computer circuits – mobile imaging – portable fuel cells	– identification chips – organic light emitting diode (OLED) display – e-commerce (B2B) – data mining
Moderate/ debatable		– electronic ink and paper – mobile remote control	– print-on-demand – collaborative business practices
small		– smart clothing	
	increasing	Indifferent/ debatable	reducing Impact on GHGs in forest cluster

Figure 1. Technology matrix.

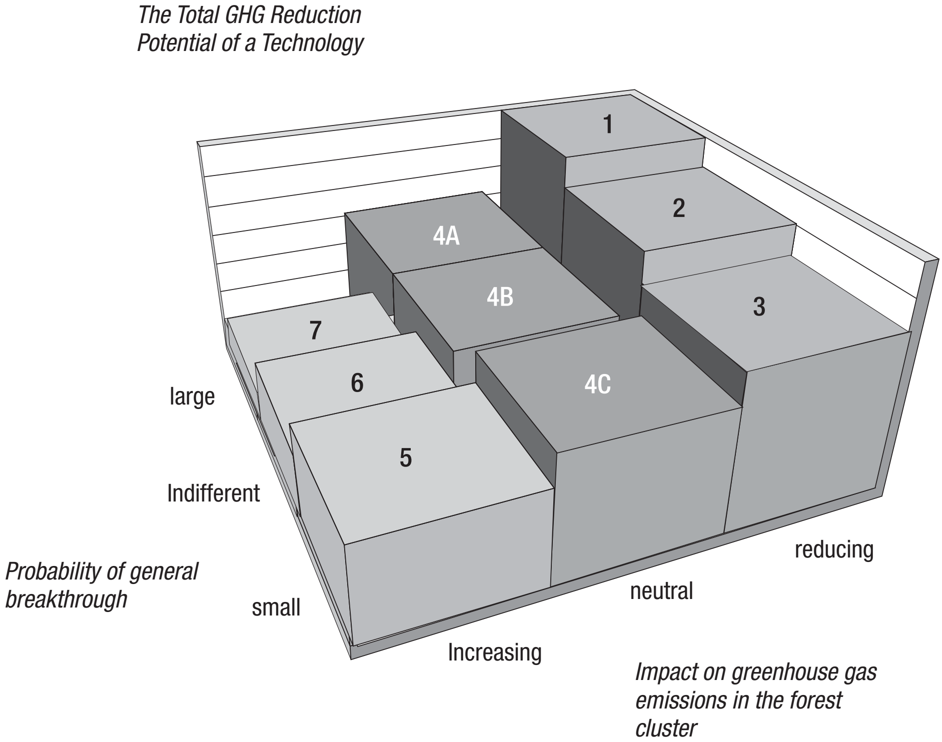


Figure 2. Kyoto staircase.

ways to the forest cluster, not expressly developed for the reduction of greenhouse gas emissions, and new or emerging so that there is rarely any data available.

The main criteria for evaluating the breakthrough potential of a technology are credibility of the technology and power of the supporting companies/institutions, analysis of the discussion around the technology, estimated costs, estimated adoption rate, user friendliness / subjective value-added, and own (Jaakko Pöyry Consulting) analysis. The main criteria for evaluating the potential impact on energy consumption and greenhouse gas emissions are estimates by the developers of the technology (greenhouse gases are rarely mentioned but energy consumption is sometimes present), analysis of the discussion around the technology, and own (Jaakko Pöyry Consulting) analysis. Of course an additional component for both sets of criteria is the ”gut feeling” – after all, we are talking about technologies with rapid development and far-reaching impacts in the future. It also has to be remembered that the impact is dependent on the size of the breakthrough.

The probability of a breakthrough is the general likelihood of a technology becoming widely used, whereas the impact on GHGs is confined to the forest cluster emissions. One important aspect of the analysis is the time frame. The time horizon for the analysis is long-term. However, we do not differentiate between those technologies which evidently approach their breakthrough already and those that may have to wait for the market to ripen in the coming few years or even decades.

3 Hot spot analysis

The first group of products from the forest industry cluster is paper and paperboard. The first representative product chosen for closer analysis is copy paper (uncoated wood free paper, office paper). Copy paper is a member of the fine paper family, and a general trend for this paper grade in recent

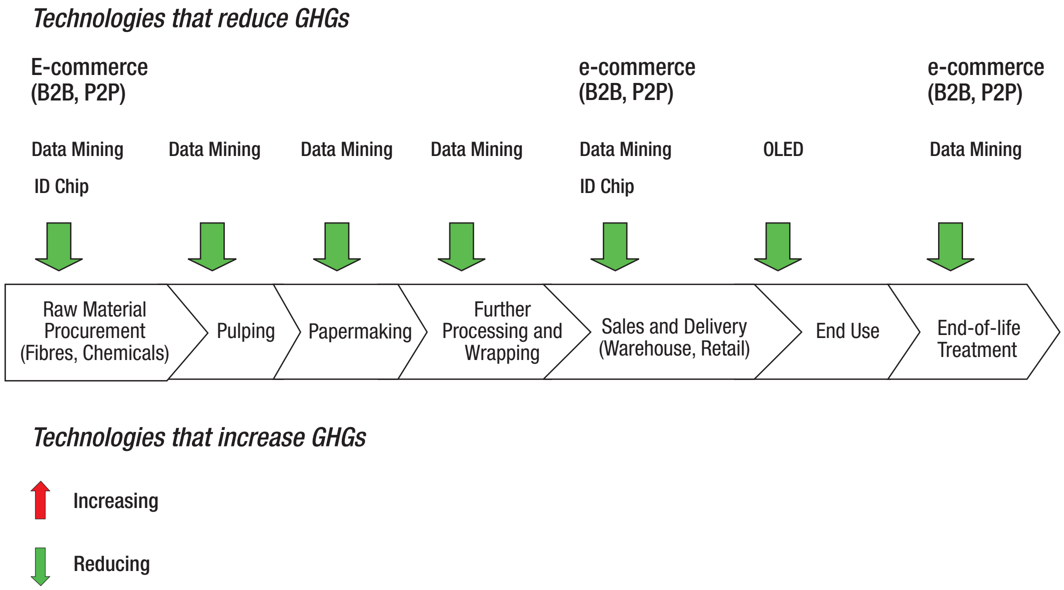


Figure 3. An example of hot spot analysis – value chain of copy paper.

years has been that its consumption has grown more than the average. All this is reality despite the increased use of laptop computers, electronic mail and information retrieval from the Internet.

The value chain of copy paper starts with raw material procurement. The main raw material is virgin wood; some recycled fibre may also be used. The pulp used for manufacturing copy paper is mostly bleached kraft pulp. By definition, wood free paper contains less than 10% of mechanical pulp. The chemicals required are mostly fillers and bleaching chemicals. The pulp is taken to a paper machine, which produces uncoated woodfree paper in reels. The next stage of further processing and wrapping refers to the cutting of paper into copy paper size and wrapping it into packages. This can be done already at the mill site, but sometimes the paper is shipped in reels to retailers for further processing. After the copy paper is wrapped it is sold and delivered to customers that are mostly retailers or large users. End-use consists of, for instance, printing and copying. After the paper has been used it is recycled back as a raw material for paper and paperboard.

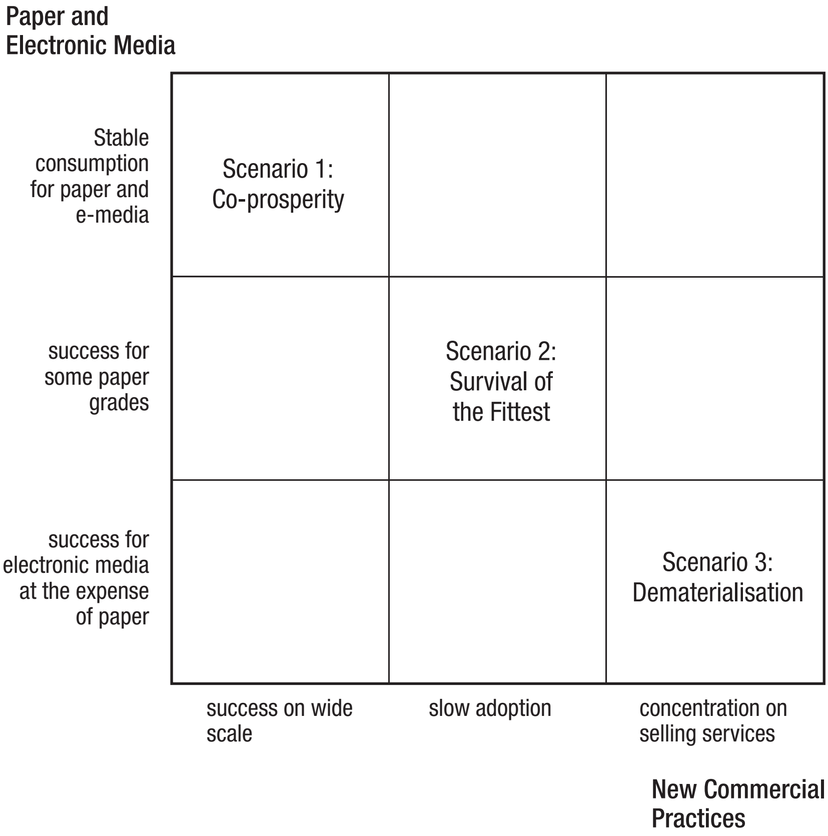
In the value chain all the other greenhouse gas reductions are assumed to come only from efficiency gains expect for the case of OLED displays. Efficiency gains are partly considered, but another possibility is also that as displays become lighter and user-friendlier, especially in laptop computers, users will do less printing in the offices and use of copy paper may actually decline. The additional reduction caused by the mentioned technologies/concepts is estimated per produced unit. The overall impact may not be as positive because the consumption and production of the grade is growing worldwide.

One limit to our analysis is the fact that, in order to make the reasoning manageable, we have to consider the impact of a given technology or concept as such, given that all other factors remain the same. This means that we do not consider changes in production volumes or in the market structure in the forest industry cluster. We also do not consider the overall impact of a technology on greenhouse gas emissions (i.e. the impact in forest industry cluster plus the impact in all other clusters). The conclusions are also conditional to the breakthrough of mentioned technologies. When all this is taken into account, the results can be considered fairly good. The energy-intensity per unit of production or production in whole is likely to fall (even if the change is small) in most cases. This conclusion is consistent with the fact that most new technologies truly aim at making processes and information flows more efficient – saving energy and other resources in doing so.

4 GHG impact scenarios

In this research project, the main indicator for greenhouse gas emissions is the change in energy consumption triggered by the studied technologies. The GHG emissions from energy consumption can be reduced by improvement of energy efficiency of appliances and processes and by structural changes in energy production. The latter is a long-term goal, which includes the adoption of energy sources with low emissions, e.g. the use of renewable energy sources on a considerably larger scale than is done today. The groups of technologies/concepts have been evaluated. The focus here is not so much on impacts of individual technologies but on their interaction and collective impact. The selected technologies are not an exhaustive list.

The future scenarios have been chosen from the most likely ones, by our judgement. The base for all scenarios is the first set of technologies: efficient computer systems. Our view is that the efficiency and capability of computer systems will continue to grow over the period that was analysed. We also feel safe in basing the scenarios on the “ultimate enabler”. The two other sets of technologies may produce more debatable outcomes. The impacts are estimated for industrialised countries where high-tech is commonly available. Most of the general growth of production and GHG emissions of the forest cluster is expected to happen in developing countries in the coming decades, due to economic growth. Hence the impacts of these technologies to the forest cluster in the industrialised



Stable consumption for paper and e-media	Scenario 1: Co-prosperity		
success for some paper grades		Scenario 2: Survival of the Fittest	
success for electronic media at the expense of paper			Scenario 3: Dematerialisation
	success on wide scale	slow adoption	concentration on selling services

Figure 4. Scenario matrix.

world are minor, in comparison to overall GHG emissions in the forest cluster. Given our choice of alternatives, the three scenarios that are finally analysed form a diagonal in the Scenario Matrix in Figure 4.

4.1 Scenario 1

The first scenario is called ”Co-prosperity” and assumes the consumption of paper to flourish alongside with the electronic media. Consumer habits are expected to change very slowly in favour of electronic media, and more radical changes (if they should be realised) are expected only when the young computer generation joins the workforce.

We expect that enhanced displays may slightly reduce printing. Business-to-business e-commerce turns to be a commonly used form of operation, and information flows, including office documents, will become increasingly digital. These two tendencies would decrease the GHG emissions in forest cluster. Opposite effects would be expected from wireless printing, which makes printing easier, and business-to-consumer e-commerce, which will increase shipping in small batch sizes. Mobile imaging can both support the use of specialty paper, thus increasing the GHG emissions of the forest cluster, or replace some paper-based media e.g. through rebound effects (i.e. money used for multimedia messaging is taken away from e.g. consumption of magazines).

4.2 Scenario 2

Scenario 2 is called ”survival of the fittest”. The development of electronic media and business practices will reduce the consumption of some paper grades but increase the demand for other kinds. Those grades that prevail are assumed to be high value added ones. As four-colour printing becomes more widely spread (e.g. prints of digital photos), quality requirements for paper will also rise. Coated papers are among the ”winners”.

The link between GHG emissions and market shares of paper grades is basically the fact that production of high quality coated grades requires more energy than production of uncoated printer paper, such as copy paper. Widespread use of multimedia messaging will increase the demand for coated paper grades. The GHG emissions increase, mostly because of larger quantities of coated paper, and partly also because there is some substitution from less energy intensive grades to coated high quality paper. B2C e-commerce will increase GHG emissions in the forest cluster foremost via increased demand for packaging material.

4.3 Scenario 3

Scenario 3 is called ”dematerialisation”. In this scenario the potential of ICT in reducing consumption of materials is fully utilised. Consumers put emphasis on the quality of life and the value added. E-commerce concentrates on selling services rather than manufactured goods. This contributes to stagnating demand of packaging board, and GHG emissions stay constant. Electronic ink and paper develop and are used increasingly. This will decrease the demand for paper with no substitution by forest cluster products, and hence GHG emissions decrease. Electronic storage of documents also decreases consumption of office paper with no substitution, which carries a similar impact.

Print-on-demand becomes a new model where resources can be used less. Collaborative business practices help to optimise the supply-chain and result in efficiency gains. The impact of increased efficiency of ICT is debatable, because the volume of devices may counteract the gains in energy-efficiency.

5 Discussion

This article provides a general overview of the development of new technologies and their impact on greenhouse gas reduction in the forest cluster. In our study, basic ICT forms the nucleus, around which an intentionally diverse group of families of technologies has been gathered. In trying to be a practical technology futurist, one has to remember to not only look at technical features but also at the potential for the required infrastructure, mind set and operational skills. We can also look at some aspects, which might undermine what we have written: assumptions, the big picture of environmental impacts, markets, and different cycles of change.

Assumptions For the sake of simplicity, we had to assume a static universe around changing technologies. Even if our conclusions about the directions of the impacts would happen to be correct, the magnitudes of the impacts might be such as to change priorities. For instance, adoption of fuel cells in trucks could significantly lower emissions from traffic – which throws argumentation based on logistics out of kilter. Our assumption is that whenever electricity consumption increases, the emissions of greenhouse gases (foremost among them CO_2) will increase. This is less true if there is a large transfer to renewable energy or nuclear power within the coming 30 years.

The big picture of environmental impacts Concern about the impacts of ICT on the environment has from being a non-issue started to raise its head. The European Union has launched several initiatives and pieces of regulation, e.g. a directive on the recycling of electronic waste. The topic of climate change is highly visible at the moment, but given the cycles of environmental issues - chlorine and emissions to water are examples of highly sensitive topics that have dropped to obscurity in a few years – the Next Big Thing may be something that is seen as completely innocuous at the moment. If so, there may be an impact on the development of the very technologies we have assessed here.

Markets As so many small technology companies during the dot-com boom found out: a supply of technology does not automatically imply a demand for the technology. The consumers decide e.g. between electronic media and paper. The so-called Harvard Law of Animal Behaviour states that “test subjects under carefully controlled laboratory conditions do what they damned well please”. Consumers, likewise, contrary to what marketers and technology creators would like to believe, choose whatever product or service they feel like choosing. In industrialised countries, ICT has become a significant item in the consumer budget. The growth has not been proportional to the increase in income. The researches investigating rebound-effects ask where the consumer takes the money for the new ICT habit. The forest cluster, like other clusters, awaits the consumers’ verdict: whose products shall pay for the ICT?

Different cycles of change Although the forest cluster generally reacts slower than the ICT industry, 30 years is a long enough period for change even under normal circumstances. Together with trends such as globalisation and consolidation, the forest cluster itself might change beyond recognition.

6 Conclusions

When seeking key technologies that would determine the scenarios, information emerged as the one common factor. Information is the one true pivot around which the possibilities to reduce GHG emissions in the forest cluster revolve.

Publications and reports made under the project

Jaakko Pöyry Consulting 2002. ECLOGUE – the Impact of Information Technology on the Reduction of Greenhouse Gas Emissions in the Forest Cluster. Tekes (Finnish National Technology Agency) /Jaakko Pöyry Consulting, August 2002.

Environmental and Energy-Related Benefits of Biotechnology in Mechanical Pulping

Biotekniset ratkaisut mekaanisen massanvalmistuksen energiataloudessa

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Abstract

Forest industry is a notable user of electric power in Finland. The main reason for this is mechanical pulping, which is very energy intensive. Energy savings in mechanical pulping would also have an indirect effect on emissions of greenhouse gases (GHG). The aims of the study were to a) study the potential for energy savings and reduction of GHGs by implementation of biotechnical methods in mechanical pulping, b) estimate the possible costs and c) assess the environmental impacts of their adoption into TMP production using the LCA methodology. Two different biotechnical methods were considered, namely fungal pretreatment of chips (biopulping) and enzyme-aided refining, both of which have shown a marked potential for energy savings in mechanical pulping. Biopulping has been studied intensively, but without experience in mill scale. Enzyme-aided refining was developed during 1990s in collaborative projects, and the method has been succesfully verified in mill scale trials.

The cost-efficiency, adoption and effects on emissions of GHGs of the biotehnical methods, compared with other competing technologies, were estimated by the EFOM model. Two different scenarios were used extending to the year 2030. In the “optimistic” scenario, cleaner technologies develop rapidly and they are adopted effectively into use, whereas in the “realistic” scenario new technologies reducing greenhouse gas emissions penetrate rather slowly into the energy and industrial systems.

The results showed that enzyme-aided refining was very competitive as compared with alternative methods, and it would be maximally penetrated into use already in the realistic scenario. Biopulping, which is technically more difficult to control and also more expensive to invest and operate, would be largely adopted in the optimistic scenario in 2020. It was shown by the LCA study that implementation of the biotechnical methods reduced total emissions of GHGs.

Tiivistelmä

Metsäteollisuus on merkittävä sähkönkäyttäjä Suomessa. Syynä tähän on suurelta osin mekaanisten massojen valmistus, joka on erittäin energiaintensiivistä. Mekaanisen massanvalmistuksen energiatalouden tehostamisella olisi siten myös kasvihuonekaasujen päästöjä rajoittava vaikutus. Tämän hankkeen tavoitteena oli a) selvittää bioteknisten menetelmien käytön mahdollisuuksia vähentää mekaanisen massanvalmistuksen energiankulutusta ja kasvihuonekaasujen päästöjä, b) arvioida käyttöönoton kustannuksia, sekä c) tutkia niiden käyttöönotosta mahdollisesti aiheutuvia ympäristövaikutuksia elinkaarinäkökulmasta (LCA). Tutkimuksessa tarkasteltiin kahta biotekniställä menetelmää, hakkeen sienikäsittelyä (biopulping) ja entsyymiavusteista hiertoa, joilla kummallakin menetelmällä on kokeellisesti osoitettu merkittävä energiansäästö-potentiaali. Biopulping -teknologiaa on tutkittu laajasti, mutta menetelmästä ei ole teollista kokemusta. Entsyymiavusteinen hierto kehitettiin 1990-luvulla kotimaisena yhteistyönä ja menetelmä on onnistuneesti testattu myös tehdasoloissa.

Bioteknisten menetelmien kustannustehokkuutta, käyttöönottoa ja vaikutuksia kasvihuonekaasujen päästöihin suhteessa muihin kilpaileviin tekniikoihin tutkittiin EFOM-mallilla, jossa käytettiin kahta erilaista kehitysarviota, skenaariota, joissa tarkastelujakso ulottui vuoteen 2030 asti. ”Optimistisessa” vaihtoehdossa uusia ja puhtaampia teknologioita tutkitaan ja otetaan nopeasti käyttöön, sen sijaan ”realistisessa” skenaariossa kasvihuonekaasujen päästöjä rajoittavien tekniikoiden käyttöönotto on hidasta.

Mallitarkastelun perusteella havaittiin, että entsyymiavusteinen hierto on kilpailukykyinen vaihtoehtoisiin menetelmiin verrattuna ja se otetaan käyttöön maksimaalisesti jo realistisessa vaihtoehdossa. Biopulping-teknologia, joka on teknisesti vaikeammin hallittava ja investointi- ja käyttökustannuksiltaan merkittävästi kalliimpi kuin entsyymiperustainen menetelmä, tulisi laajaan käyttöön optimistisessa kehitysvaihto-ehdossa vuodesta 2020 alkaen.

Elinkaaritarkastelussa todettiin, että bioteknisten menetelmien käyttöönotto vähentää kasvihuonekaasujen kokonaispäästöjä. Sienikäsitelty hake lisää valkaisutarvetta, jolloin päästöt kasvavat valkaisukemikaalien valmistusprosesseissa, mutta niiden osuus kokonaispäästöistä on kuitenkin vähäinen.

1 Introduction

Generally it is stated that biotechnology has clear environmental advantages and is economically competitive in a growing number of industrial sectors. Implementation of biotechnical innovations into industrial use is commonly considered to reduce material and energy consumption, as well as pollution and waste generation for the same level of industrial production. However, studies on benefits or “cleanliness” of biotechnical methods in process industry are rare (OECD 1998).

Sustainable development in industry is encouraged by governmental actions, increasing R & D resources and public awareness. The Kyoto agreement on greenhouse gas reductions is an example of a political push in favour of sustainable development and more rapid diffusion and application of new innovations in industry.

One important means of integrating environmental issues into industrial design and operations is the adoption of Life Cycle Assessment (LCA), which so far is the best approach to evaluate cleanliness. Because of the limited availability of data on industrial scale application of biotechnical methods in mechanical pulping, the LCA done in this study focuses mainly on the CO_2 reduction potential and respective impacts on the climate.

The aims of the study were to a) study potential for energy savings and reduction of GHGs by implementation of biotechnical methods in mechanical pulping, b) estimate the possible costs and c) assess the environmental impacts of their adoption into TMP production using the LCA methodology. Two different biotechnical methods were considered, namely fungal pretreatment of chips (biopulping) and enzyme-aided refining, both of which have shown marked potential for energy savings in mechanical pulping.

2 Forest industry in Finland

The production of paper and board in Finland has increased steadily from 1970’s and in 2000 the annual production was over 1,350 000 t (Forest Industries Federation 2002). Overall production of paper products has been predicted to grow during the next twenty years, and the increment will largely be concentrated on wood containing paper and paperboards (Fig. 1, MTI 2001a).

Competitiveness of the Finnish pulp and paper companies is to a large extent based on high quality wood-containing writing and magazine paper grades, like SC and LWC. This means that production of mechanical pulps, which are essential pulp components in these paper grades, is also expected to increase. A growing portion of mechanical pulp is estimated to be produced as thermomechanical pulp (TMP) instead of groundwood pulp (MTI 2001a). Production of groundwood pulp will increase only slightly and this shift in favour of TMP will have a clear energy related impact.

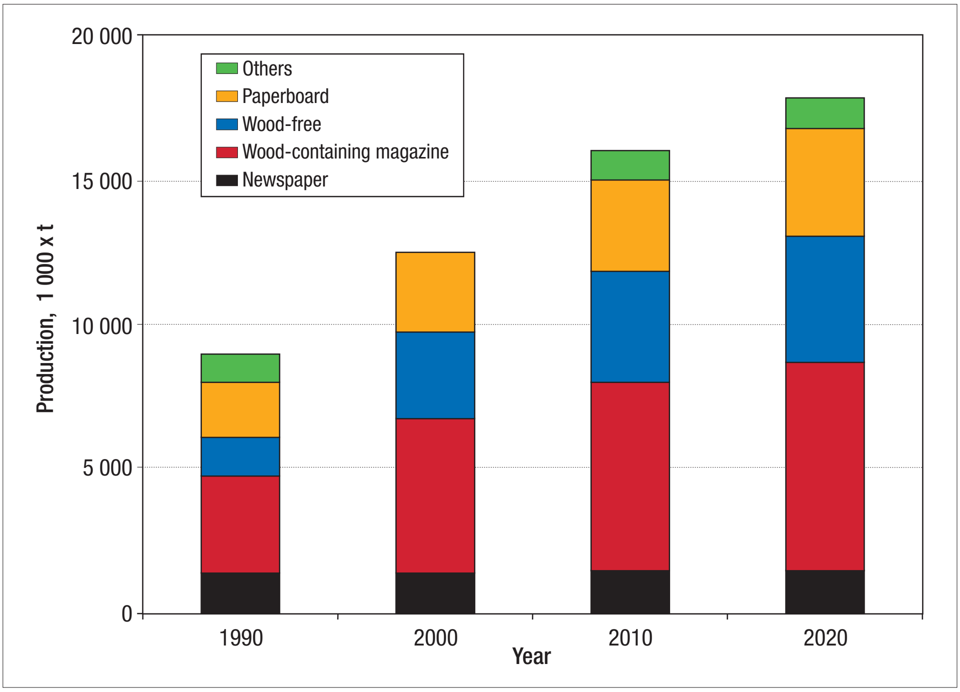

Figure 1. Predicted production of paper and board during 1990–2020 (MTI 2001a).

In 1998 the consumption of electricity for mechanical pulping in Finland was 9.55 TWh, which corresponded to 40% of the overall electricity consumed in the forest industry (MTI 2001a). During the next decades, the annual consumption of energy (GWh/a) within the forest industry is estimated to increase gradually in conjunction with paper and board production capacity (MTI 2001a).

During the last decade, plenty of research efforts have been focused on reduction of specific energy consumption (SEC) of mechanical pulping in Finland and also worldwide. Unfortunately, there seems to be no sign of a new superior method or a technology heap in mechanical pulping (Sundholm 1999). It is evident that in the near future SEC in mechanical pulping and paper production will be decreased within small steps, as new production machinery and technology are adopted. It is expected that, via optimisation of the refining process and the control system, some decrease of SEC can be obtained within a few years (MTI 2001a). Implementation of new technology and production methods, including biotechnical methods, into mill processes has to be based on cost efficiency, as compared with prevailing and other competing technologies.

3 Biotechnology and mechanical pulping

The general goals of pulp and paper industry today are to increase the cost efficiency, to develop environmentally benign processes and to improve the product quality. The main research and development issue in mechanical pulping has for years been in reduction of energy consumption in refining. Within this issue, biotechnical research has been focused on two different approches, i.e. biopulping with fungi and enzyme-aided refining of coarse pulp or rejects (e.g. Akhtar *et al.* 1998, *Pere et al*. 2000, 2002). Biopulping involves fungal pretreatment of chips prior to main refining, whereas in enzyme-aided refining a portion of screened pulp is subjected to enzymatic treatment

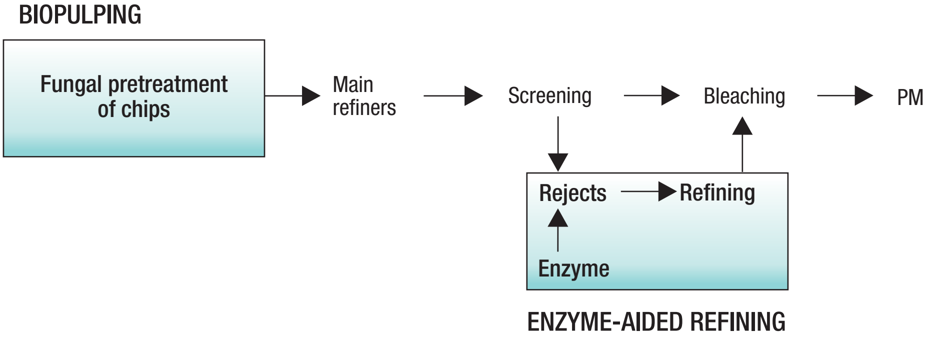

Figure 2. Principles of the biotechnical methods for mechanical pulping.

in order to enhance reject refining (Fig. 2). Both of the methods have proved to be effective when aiming at energy savings in mechanical pulping. Biopulping has been tested in laboratory and pilot scales with promising results, but research efforts are still needed to verify the concept in mill scale. Instead, successful mill scale trials with the enzymatic treatment of reject pulp have been performed and the method is approaching commercial use in near future (Pere *et al*. 2002).

3.1 Biopulping

In biopulping, wood chips are treated with a selected micro-organism, usually a white-rot fungus, prior to mechanical pulping. The biopulping organism attacks wood lignin and softens wood chips. This results in substantial energy savings of refining. Depending on the organism and wood species, the reported energy savings have been in the range of ca. 20–40% after two-week treatment

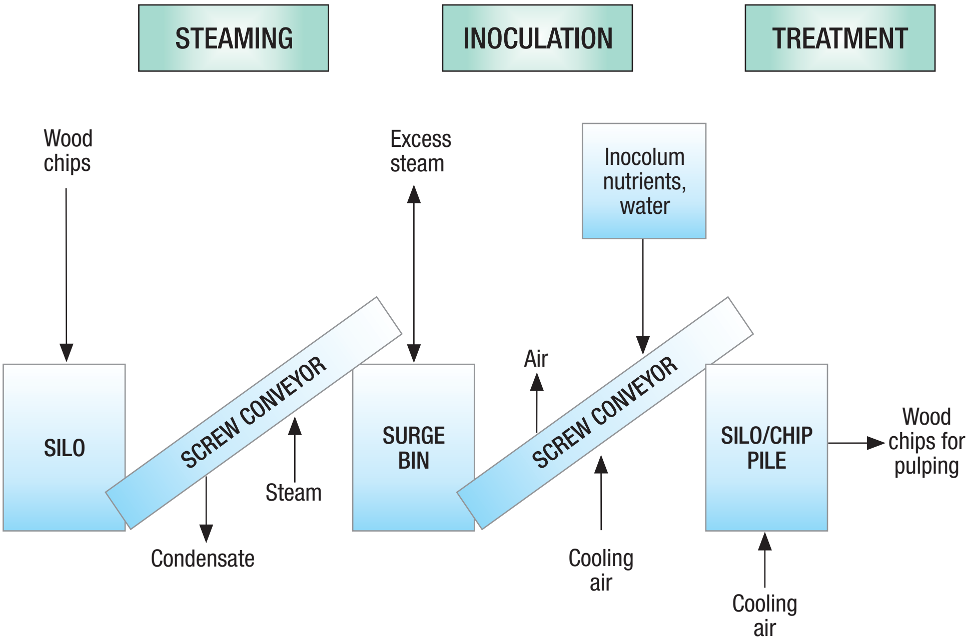

Figure 3. A diagram of biopulping process.

(Akhtar *et al.* 1998, Scott *et al.* 1998b). Paper strength properties have been shown to improve after biopulping. The main drawbacks of the treatment are yield and brightness losses (Akhtar *et al.* 1997a, Akhtar *et al.* 1998). Yield loss is dependent on the fungus and treatment time. A two-week treatment with e.g. *Ceriporiopsis subvermispora* can cause 2% yield loss (Scott *et al.* 2002). Fungal pretreatment of wood chips significantly reduces the brightness of the resulting mechanical pulp. To gain the same level of brightness as in normal mechanical pulp, fungal treated pulps need additional bleaching.

Biopulping with the fungal strains available today cannot be performed with intact wood chips (Akhtar *et al.* 1998). Indigenous, natural micro- organisms on wood chips inhibit growth and colonisation of the inoculated fungus reducing its modifying power on chips. Bisulfite treatment or short steaming of wood chips prior to inoculation has been shown to allow the proper start up of fungal growth on chips.

An operating production line including a biopulping step has not yet been demonstrated. In this work an industrial production line for a daily output of 600 tons of treated chips was described and preliminarily designed (Kallioinen *et al.* 2002). The main process stages of biopulping are presented in Figure 3. Reliable operation in Nordic climatic conditions using spruce as the raw material was the guiding principle in planning work. Available background information from literature (Scott *et al.* 1998a, Akhtar *et al.* 1997b) and discussions with component manufacturers (Metso Woodhandling, Fläkt Oy, Tankki Oy) were utilised to aid the planning work. Design work was performed for two options, namely, for the treatment in silos and piles.

A preliminary cost evaluation for biopulping was carried out (Kallioinen *et al.* 2002). Investment costs for the model production line (600 t/d) were calculated. Investment costs for the treatment in silos were twice as high as in piles, but in silos the homogeneity and quality of the treatment is expected to be better due to more controlled growth conditions for the fungus. The additional need of bleaching chemicals, electricity and nutrients were shown to be the main factors contributing to the operating costs of the biopulping process.

3.2 Enzyme-aided refining of mechanical pulp

In addition to microorganisms, enzyme preparations can also be applied in modification of wood raw material prior to mechanical pulping. In enzyme-aided refining an enzyme preparation, free of living cells, is used for modification of coarse pulp or rejects prior to reject refining. The concept of enzyme-aided refining was developed during 1990's at VTT Biotechnology in collaboration with the Laboratory of Pulping Technology at Helsinki University of Technology (Pere *et al.* 2000, 2002). The main aim was to obtain energy savings in refining while retaining good pulp properties. The study started with screening of suitable enzyme(s) for pretreatment of coarse pulp prior to laboratory scale refinings with a disk-refiner. Main attention was paid on enzymes acting on carbohydrates, i.e. cellulases and different types of hemicellulases, instead of lignin-modifying enzymes.

As a result of the screening and testing of several purified enzymes and their mixtures in laboratory scale refinings a cellulase, namely cellobiohydrolase I (CBH I), was found to be the most promising. When coarse TMP (CSF 400–600 ml) was pretreated with CBH I for a few hours, energy savings between 15 and 20% were obtained in the successive reject refining (Pere *et al.* 2000). One primary advantage of the method as compared with the competing technologies was that the reduction in SEC was obtained without any harmful effects on pulp quality. In fact, improvement of strength properties of pulp was demonstrated when coarse rejects devoid of fines (CSF 600–650 ml) were treated. In addition, no deterioration of sheet optical properties, e.g. decrease of brightness, was detected due to the enzymatic pretreatment. The potential of this enzymatic method was also tested in pilot scale trials and later on mill scale (Pere *et al.* 2002). Integration of the enzymatic treatment into a TMP mill is shown in Fig. 4. No negative downstream effects of enzymatic treatment are foreseen.

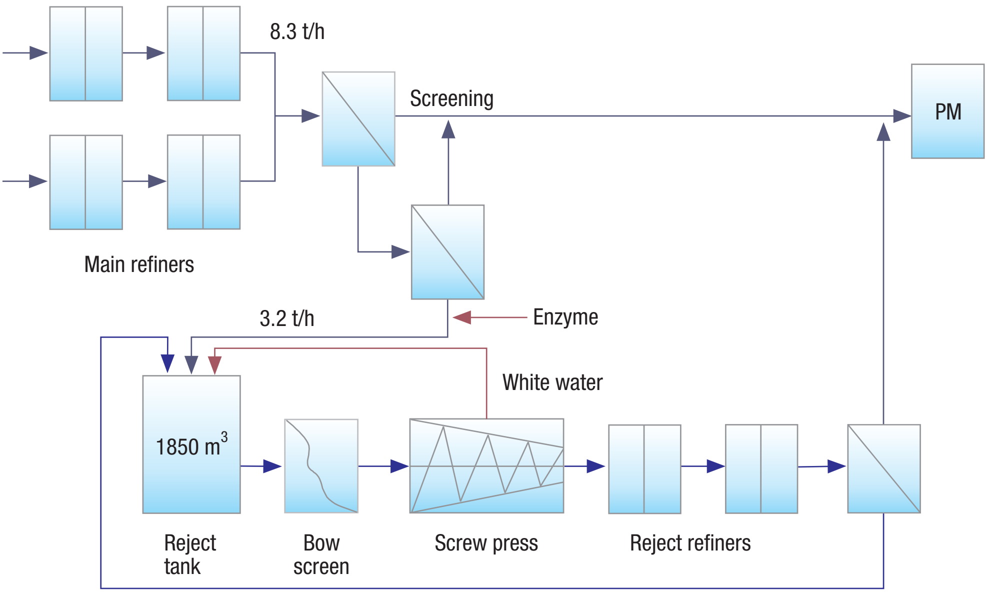

Figure 4. Implementation of the enzymatic treatment into TMP mill.

4 Scenario studies

The potential of biotechnical methods for energy savings and reduction of greenhouse gas emissions in Finland was estimated using scenario studies. The possible future developments were assessed for two alternative scenarios:

- "Realistic" development: International climate change mitigation measures evolve rather slowly. There are no significant changes in the support for the development and commercialisation of cleaner technologies. As a result, new technologies reducing greenhouse gas emissions penetrate rather slowly into the energy and industrial systems.
- "Optimistic" development: As a result of accelerating climate change mitigation measures, both internationally and within Finland, cleaner technologies develop rapidly and they are taken effectively into use. This assumes also increased support for the development and commercialisation of technologies reducing greenhouse gas emissions.

In the Kyoto protocol, Finland has committed herself to a stabilization of greenhouse gas emissions at their 1990 level. The target is challenging, as the total energy consumption in Finland has grown during 1990's by 16%, and the growth has been estimated to continue also in the future. In 2001, CO_2 emissions from fuel combustion were 60 million tonnes CO_2, whereas in 1990 they were 53.9 million tonnes CO_2 (Statistics Finland 2002). A decreasing trend in CH_4 and N_2O emissions kept the Finnish total greenhouse gas emissions below the Kyoto target during 1990's.

Figure 5 shows the dominating sources of CO_2 emissions in Finland. In the figure the relative importance of CO_2 emissions from combustion in the energy and industrial sectors in total greenhouse gas emissions in Finland is also illustrated. The Industrial sector is the second largest single CO_2 emitting sector in Finland.

The efficiency of energy and electricity saving measures in reducing greenhouse gas emissions depends on the fuel structure used. For instance, if electricity for the process is produced with coal, electricity savings will result in a reduction of of CO_2 emissions by about about 800–900 gCO_2/kWh. In the other extreme, if the energy used in the process were produced by carbon-free sources, such as (sustainable use of) biomass or hydro-

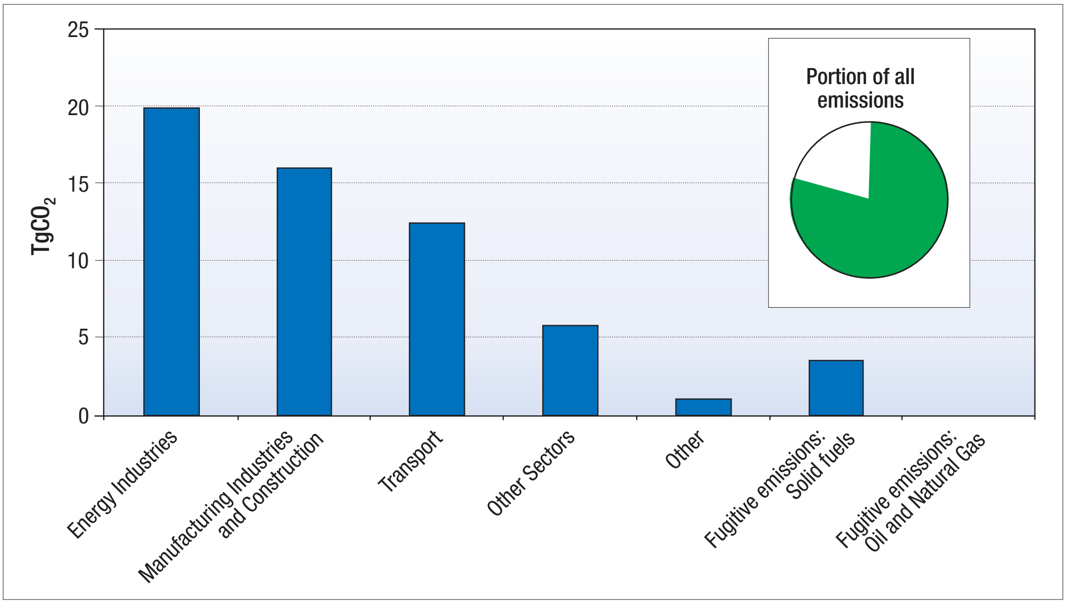

Figure 5. CO_2 emissions (58.5 Tg) in the energy sector by main source categories and their portion of all anthropogenic greenhouse gas emission in Finland in 2000. Source: VTT, SYKE.

power, there would not be any direct benefit in CO_2 emissions. The fuel structure is also prone to change over time, thus changing the CO_2 reduction efficiency as well.

In Finland, energy saving operations affect mainly the amount of electricity bought from outside. The energy needs of the process industry are quite even throughout the year. The energy saving measures will thus reduce the amount of marginal condensing power needed. In the Nordic countries, the marginal condensing power used is presently mainly coal power with specific CO_2 emissions at about 800–900 gCO_2/kWh. If energy saving measures would reduce the use of natural gas in combined cycle power plants, the specific CO_2 emission savings are about 300 gCO_2/kWh.

In this project the effect of biopulping techniques on greenhouse gas emissions in Finland was assessed using the EFOM-ENV energy system model. The EFOM-ENV is a linear optimizing energy system model used at VTT Processes (Lehtilä and Pirilä 1996, Lehtilä and Tuhkanen 1999). The EFOM model calculates energy supply and demand with user-defined pre-conditions and constraints, such as fuel prices or total energy demand. The model determines for any study period the cost-optimal mix of fuels and technologies with given boundary conditions, such as emission limits. In this work, EFOM was used to analyse the cost-effectiveness of biotechnical methods in pulping as a measure of greenhouse gas reduction in comparison to other available measures. An energy system model is required in order to comprehensively assess all the reflections of single additional techniques on the whole energy system.

In the scenario modelling work, the assumptions of the KIO2 scenario of the recent National Climate Strategy of the Finnish Government were used (MTI 2001a, b). In the scenarios it was assumed that Finland would meet the Kyoto obligation on the reduction of greenhouse gases, which is the stabilization of greenhouse gas emissions at the 1990 level during the period 2008–2012. After this period it was assumed that the emissions should be further reduced. A reduction target of –20% from the 1990 level was set for the year 2030. In the model study, it was assumed that after 2010 the energy taxation structure would be gradually transformed towards CO_2-based taxation instead of the present structures.

The EFOM model was used to find the cost-optimal path for reaching the emission targets. The penetration of biotechnical methods in mechanical pulping was determined by their cost-effectiveness in comparison to other greenhouse gas emission reduction options. In other words, biotechnical methods were not "forced" to enter the market unless they proved cost-effective in comparison to other methods available in the total energy system. In addition, it was assumed that in the future these biotechnical methods would be applicable also in the production of coarser grades, *e.g.* for newspaper production. The potential of biopulping was mainly investigated with the chip pile option, which has considerably lower investment costs than the silo treatment option.

With the conventional assumptions on the development of biotechniques and the required chemical uses, only the enzyme-aided pulping turned out to be cost-effective in comparison to other methods available in the total energy system until the year 2020. By 2030, also biopulping in newspaper production would become economical in the "Realistic" scenario. This is due to the lower additional bleaching costs assumed in comparison to finer paper grades.

When the "Optimistic" scenario on the development of biotechnical methods was assumed, biopulping started penetrating rapidly the sector in 2020. Figure 6 shows the cost-effective penetration of the different methods with both scenarios and the total mechanical mass production scenario assumed calculated with the EFOM model (Forest Industries Federation 2002, MTI 2001a, b).

According to the model, the total electricity consumption would increase from 30.5 TWh in 2010 to 34.1 TWh in 2030 without taking benefit of the biotechnical methods (MTI 2001b). The conventional scenario for biotechnical methods would yield about 1% saving in the total electricity consumption of the total forest industry sector in Finland by 2030. The optimistic scenario for biotechnical methods results in about 5% saving in the total electricity consumption of the forest industry sector in Finland by 2030.

In the model study, the biotechnical methods compete with all the reduction options, and in the cost-optimal solution the adoption of biotechnical methods may allow to exclude some of the most expensive reductions in other sectors of the society. In the scenarios studied, the biotechnical methods allowed to exlude mainly some of the expensive

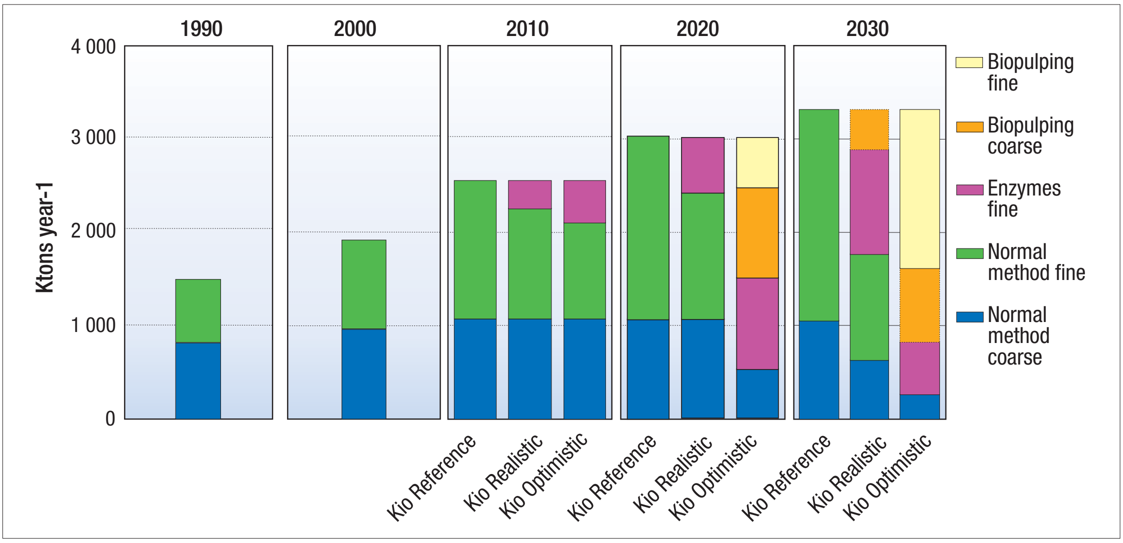

Figure 6. Development of mechanical pulp production in Finland during 1990–2030, and penetration of the different methods in the scenarios studied.

emission reduction options in the service sector. As a result of this substitution effect, the net impact on Finland's total emissions remain much smaller than the impact in the forestry sector alone. Instead, the main net impact is a decrease in the average emission reduction costs. The total greenhouse gas emission reductions in Finland were 0.1 $TgCO_2$ with the conventional technology scenario and 0.6 $TgCO_2$ with the optimistic technology development scenario, *i.e.* 0.2% and 1.0% of total greenhouse gas emissions.

The total emission reduction costs (discounted to the present value) during the period studied decreased with biotechnical methods by about 33 million € in the "Realistic" scenario and by about 62 million € in the 'Optimistic' scenario. The marginal costs for further greenhouse gas emission reductions with the biotechnical methods available were about 47 €/ton CO_2-eq. Figure 7 shows the development of Finnish greenhouse gas emissions with the scenarios studied.

The EFOM model calculations assumed a 30 years technical lifetime for enzymatic pulping and 35 years for biopulping. This approximate technical lifetime is a considerably longer time horizon than what enterprises usually base their investments on. Therefore, the cost-effectiveness results should be viewed from the point of national economy rather than that of a single enterprise.

The international mitigation of climate change is expected to change the energy and industrial systems profoundly in long run. Already in the short term with the recent EU proposal on greenhouse gas emission trading within the EU, envisaged to start in 2005, CO_2 emissions may develop into an article of trade with a market price. In this case, calculations on cost-effectivenes of energy-saving investments should take into account also the value of the CO_2 emissions avoided (as was done in the EFOM model calculations).

The potential of biopulping was mainly investigated with the "chip pile" option, which has con-

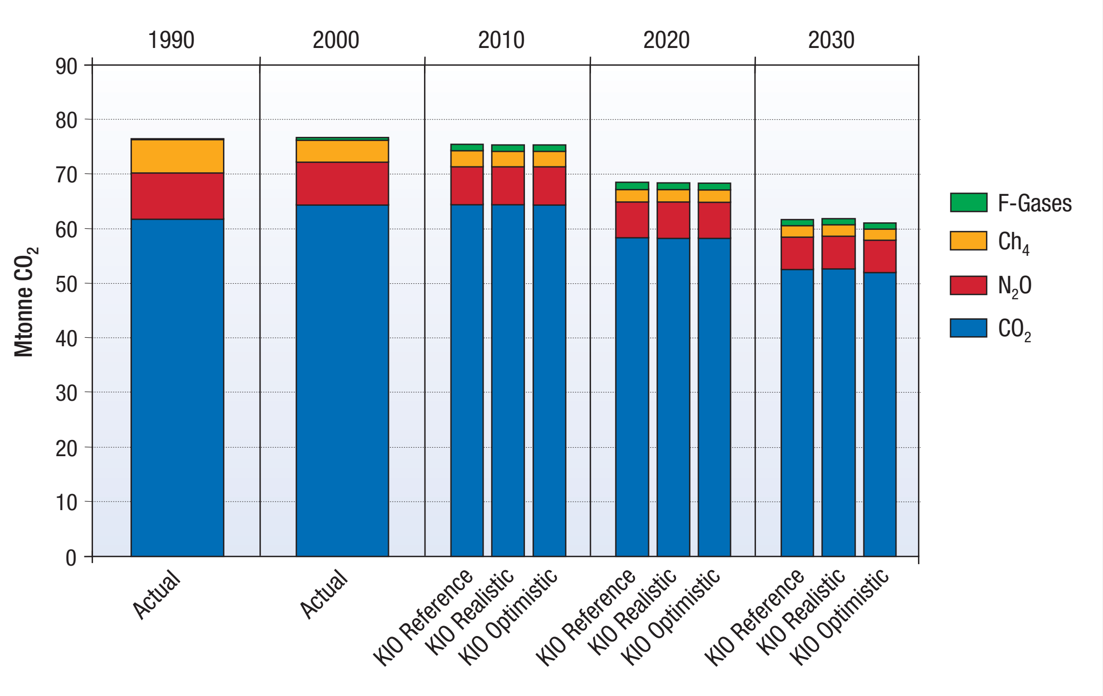

Figure 7. Finnish greenhouse gas emissions during 1990–2030 in the scenarios studied.

siderably lower investment costs than the "silo treatment" option. With the "Realistic" scenario, it is unlikely that the biopulping technique with the Silo treatment would have become cost-effective. In the "Optimistic" scenario, biopulping techniques penetrated their maximum share allowed. As the investment costs are discounted over the whole payback time and other costs (such as the extra bleaching needed) form a significant part of the total cost per tonne produced, also the Silo treatment option could become cost-effective in long run, especially if pilot experiments indicate that a better pulp quality or shorter treatment times can be achieved with the "silo treatment".

It has been estimated that other options, such as improved process control and further adjustments in refining process, would also lead to similar unit reduction costs in pulping as biotechnical methods (MTI 2001a). Biotechnical methods may reduce the economic potential of other energy saving measures for the same process. It should, however, be noted that adoption and benefits of biotechnical methods are highly plant-specific.

5 Environmental impacts of mechanical pulping (LCA)

The life cycle assessment (LCA) methodology (SFS-EN ISO 14040, 14041, 14042, 14043) was applied to study environmental loads and impacts of mechanical pulping (TMP). This LCA study on TMP includs production of energy, bleaching chemicals and biotechnical products connected with the main phases of mechanical pulping. The main phases of TMP production are debarking, chipping, refining and bleaching. The goal of the life cycle assessment (LCA) was to produce information on the environmental impacts of the chosen biotechnical methods if implemented in traditional TMP production.

The traditional TMP process servs as a reference for the modified processes, i.e. enzyme-aided refining (ENZYME) and biopulping (BP REAL & BP OPT). The LCA analysis is performed according to the two diffferent scenarios, realistic (REAL) and optimistic (OPT) mentioned in the previous chapter. The results are calculated corresponding to one metric ton (t) of bleached mechanical pulp.

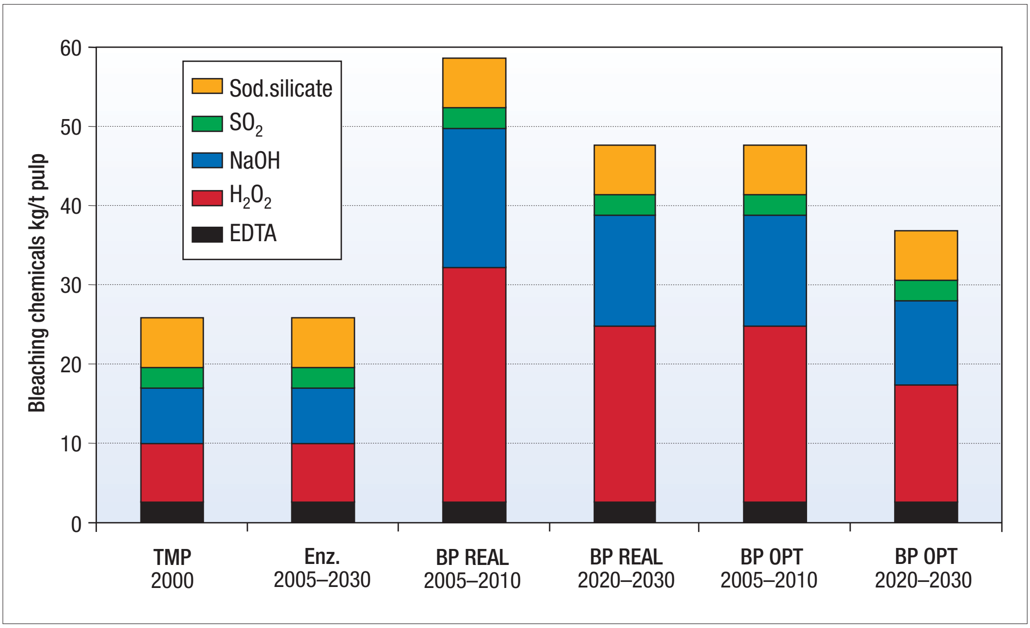

Figure 8. Estimated use of bleaching chemicals (kg/t of bleached pulp) in different mechanical pulping systems Enz. (enzymes), BP (biopulping).

The system boundaries begin from the wood yard and end before papermaking, where mechanical and chemical pulps are mixed with paper additives.

The data for the biotechnical unit processes were obtained from VTT Biotechnology, literature and relevant companies, whereas information on the TMP process came from UPM-Kymmene Rauma Paper Mills. Inventory results include consumptions of bleaching chemicals and energy, as well as emissions causing global warming, acidification and photochemical formation of tropospheric ozone (IPCC 1995, Lindfors *at al.* 1995, Hauschild & Wenzel 1998). The results deal only with emissions to air, because at the moment there are no available data on eventual wastewater loads caused by the biotechnical methods.

Consumption data of bleaching chemicals, electricity and heat in the mechanical pulping systems are presented in Figs. 8 & 9. A significant increase of bleaching chemicals can be noted in the beginning of implementation of biopulping technology, but due to R & D efforts it is estimated to decrease later. The enzyme-aided refining does not affect the consumption of bleaching chemicals. The biotechnical steps, i.e. the fungal treatment of chips, comprise 12–14% of the total energy use of the considered systems. The energy savings are in the order of 0,13–0,6 MWh/t of bleached pulp

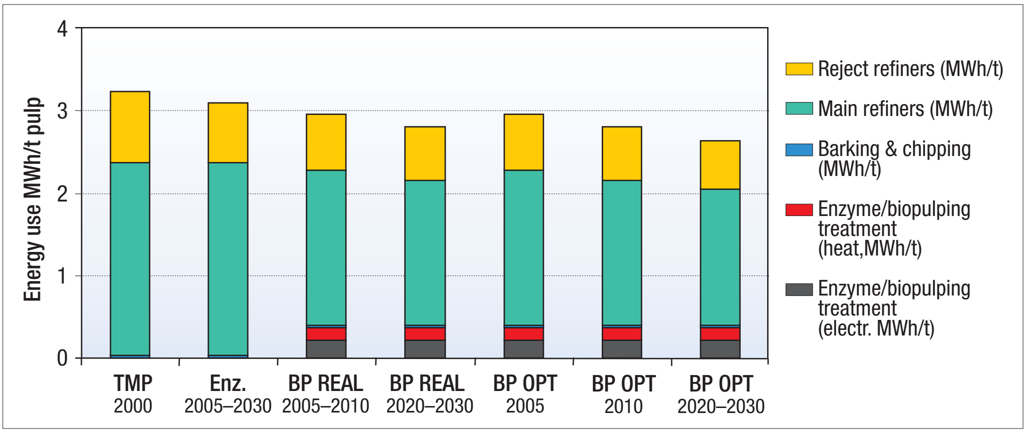

Figure 9. Estimated consumption of electricity and heat (MWh/t) in different pulping systems Enz. (enzymes), BP (biopulping).

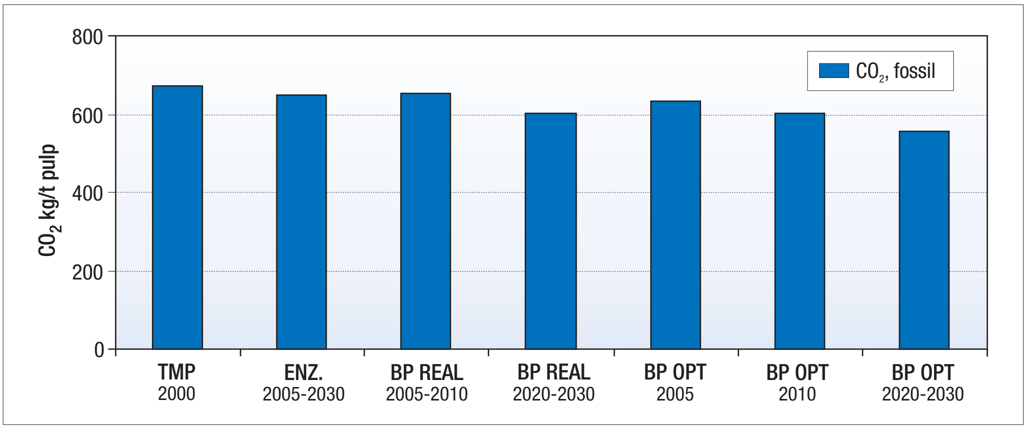

Figure 10. CO_2 emissions as kg/t of bleached pulp in the mechanical pulping systems Enz. (enzymes), BP (biopulping).

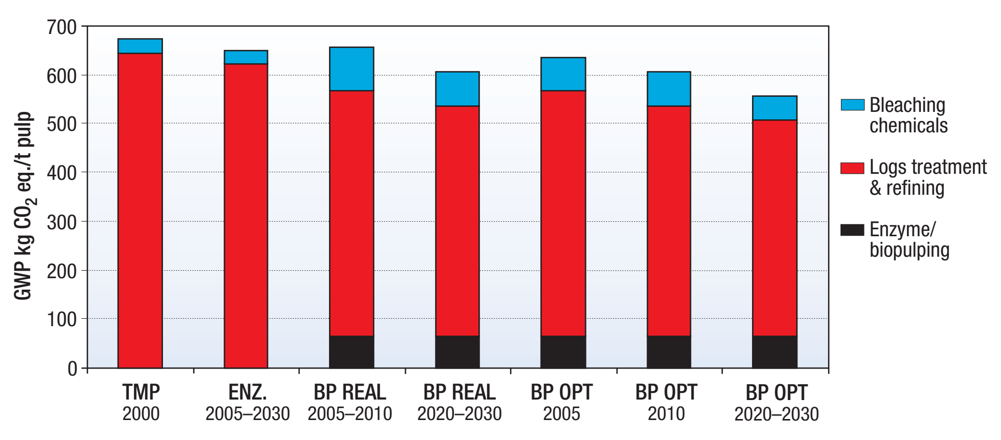

Figure11. Global warming potentials expressed as equivalents of kg CO_2/t of bleached pulp Enz (enzyme), BP (Biopulping).

when taking into account the steam energy used in the biopulping systems.

The total greenhouse gases (CH_4, CO_2 and N_2O) released by the modified TMP processes are composed almost totally of the CO_2 emissions (Fig. 10). They are mainly due to energy production processes and combustion of fossil fuels. In biopulping, the fungal treatment of chips causes about 10%, refining 77% and the bleaching chemicals about 13% of the total CO_2 emissions of the system. The shares of the N_2O and CH_4 emissions are small and they originate almost totally from energy production chains of bleaching chemicals. The emissions causing acidification and photochemical formation of tropospheric ozone follow almost the same trend as the emissions of the greenhouse gases (Kallioinen *et al*. 2002).

The electricity savings in refining reduce the total emissions. It can be emphasised that the production chains of the enzyme and fungal inoculum form only a minor part of the total greenhouse gas emissions released in mechanical pulping systems. However, the increased use of energy in fungal treatment of chips causes emissions.

The global warming potentials were also calculated as equivalents of CO_2 (Fig. 11). The share of transports of chemicals is small compared with the share of logs treatment & refining. The shares of bleaching chemicals and enzyme/biopulping are quite equal forming 9–13% of each from the total system. The calculated potentials of global warming, acidification and photochemical formation of tropospheric ozone follow the same trend as the corresponding total emissions. The need of steam and electricity in storing of chips and fungal treatment increase emissions and environmental impacts in biopulping. Also in biopulping, the production chains of increased use of bleaching chemicals generate emissions, but later developments of the biopulping technology is expected to lower them under the present level.

Based on the LCA study the following conclusions can be made:

- total air emissions decrease due to implementation of the biotechnical methods
- air emissions from the production chain of the enzyme and fungal product are low
- air emissions from the production chains of bleaching chemicals increase due to increased use of H_2O_2 and NaOH in biopulping
- wastewater loads are expected to increase in biopulping, but the calculations are omitted due to unavailability of relevant data at the moment.

6 Conclusions

The results show that enzyme-aided refining is economical and competitive as compared with alternative methods in improving energy economy of mechanical pulping. Biopulping can also be competitive in spite of rather high investment costs, but it still needs research efforts in order to be largely adopted in industrial use.

The LCA study shows that implementation of biotechnical methods in mechanical pulping will reduce the total air emissions including GHGs due to decreased energy use in refining. However, the air emissions from the production chain of bleaching chemicals and fungal treatment of chips increase due to increased needs of chemicals and energy in the biopulping system. However, the air emissions from the production chains of the enzyme and fungal products are low. More knowledge, continued research efforts and large-scale trials are though needed to assess wastewater loads and to improve the quality of the data on the environmental burdens when utilising biotechnical methods in mechanical pulping.

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Kallioinen, A., Pere, J., Siika-aho, M., Viikari, L., Mälkki, H., Lehtilä, A., Syri, S., Thun, R. 2002. Environmental and energy-related benefits of biotechnology in mechanical pulping. VTT Publications xx. Espoo, Finland. (to be published).

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Industrial Ecology and the Reduction of Greenhouse Gas Emissions

Teollinen ekologia ja kasvihuonekaasupäästöjen vähentäminen

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Abstract

Industrial ecology is a relatively new concept emphasizing systems approach in studying the interaction of natural and industrial systems and seeking ways to redesign industrial systems to reduce the ecological impact to levels the natural system can sustain. It can be suggested that climate change mitigation is a challenge that requires systems approach and novel ideas related to technologies and practices and their implementation and diffusion.

The aim of the project was to study the potential of industrial ecology in bringing novel insights into climate change research and greenhouse gas control. The project was realised by reviewing literature and activities in the field of industrial ecology and by interviewing experts from universities, research institutes, ministries and industry. In addition to this two case studies were carried out: one related to regional energy system and one to e-commerce and food production and consumption system. The results of the project were presented in a workshop that formed a part of the project.

The unique features of industrial ecology compared with other frameworks and ideas are the use of natural systems as a metaphor and guide in designing industrial systems and the search after innovative system level solutions to complicated environmental problems. Closing the loops by using waste material of one industry or facility as a raw material of another is considered by many to be a central theme of industrial ecology. As the case study on regional energy system shows, this type of solutions are already to some extent a normal practice in industry and have led to significant energy savings and greenhouse gas emission reductions. Industrial ecology could be helpful in identification and implementation of innovative future system level solutions, if it were able to create new kind of cooperation between researchers studying climate change and its mitigation from different perspectives and at different system levels, and to enhance the interaction between the producers and users of research results.

Tiivistelmä

Teollinen ekologia on suhteellisen uusi käsite, joka painottaa systeemilähetymistapaa luonnon ja teollisten systeemin vuorovaikutuksen tutkimisessa ja teollisen systeemin suunnittelussa sellaiseksi että sen ympäristövaikutukset eivät ylitä luonnon kantokykyä. Ilmastomuutoksen hillintä on haaste, joka vaatii systeemilähestymistapaa ja uusia ideoita liittyen teknologioiden ja toimintatapojen kehitykseen, käyttöönottoon ja leviämiseen.

Projektin tavoitteena oli selvittää teollisen ekologian mahdollisuudet tuoda uusia näkökulmia ilmastotutkimukseen ja ratkaisuja kasvihuonekaasupäästöjen vähentämiseen. Projekti toteutettiin käymällä läpi kirjallisuutta ja haastattelemalla asiantuntijoita yliopistoista, tutkimuslaitoksista, hallinnosta ja teollisuudesta. Lisäksi tehtiin kaksi case-tarkastelua: toinen liittyen alueelliseen energiajärjestelmään ja toinen sähköiseen kauppaan ja ruuan tuotanto- ja kulutusjärjestelmään. Projektin tulokset esiteltiin tilaisuudessa, joka muodosti osan projektin toteutusta.

Teollisen ekologian ominaispiirteinä muihin käsitteisiin verrattuna voidaan pitää luonnon käyttöä vertauskuvana ja ohjenuorana teollisen systeemin tarkastelussa ja suunnittelussa sekä pyrkimystä löytää innovatiivisia järjestelmätason ratkaisuja monimutkaisiin ympäristöongelmiin. Kiertojen sulkemista käyttämällä toisen jätettä toisen raaka-aineena pidetään teollisen ekologian keskeisenä teemana. Alueellisen energiasysteemin tarkastelu osoittaa, että tällainen toiminta on jo jossain määrin normaalia teollisuudessa ja että sen avulla on säästetty energiaa ja vähennetty kasvihuonekaasupäästöjä metrkittävästi. Teollinen ekologia saattaisi edesauttaa tulevaisuuden innovatiivisten järjestelmätason ratkaisujen tunnistamista ja toteutusta, mikäli se pystyisi lisäämään yhteistyötä ilmastomuutosta ja sen hillintää eri näkökulmista ja eri järjestelmätasoilla tutkivien tahojen välillä sekä tutkimustuloksia tuottavien ja niitä käyttävien tahojen välillä.

1 Introduction

Industrial ecology is a relatively new concept emphasizing systems approach in studying the interaction of natural and industrial systems and seeking ways to redesign industrial systems to reduce the ecological impact to levels natural system can sustain. A new field needs to show that it generates novel insight, practical advantage or some leverage over problems that are not provided by other frameworks or ideas (Lifset 2002).

It can be suggested that climate change mitigation is a challenge that requires systems approach and novel ideas related to technologies and practices and their implementation and diffusion. The aim of the project was to study the role of industrial ecology in this respect. The project was realised by reviewing literature and activities in the field of industrial ecology and by interviewing experts from universities, research institutes, ministries and industry. In addition to this two case studies were carried out: one related to regional energy system and one to e-commerce and food production and consumption system. The results of the project were presented in a workshop that formed a part of the project.

2 What is industrial ecology

2.1 History and development

The concept of industrial ecology appeared in the literature for the first time in 1970's. The current content of it, however, originates to great extent from the article "Strategies for Manufacturing" in Scientific American by Robert Frosch and Nicolas Gallopolous (1989) and article by Hardin Tibbs (1992). More about history of industrial ecology can be read from literature (Erkman 1997).

Earlier industrial ecology was often used almost synonymously with industrial metabolism. Industrial metabolism describes the industrial system as a living complex organism, feeding on natural resources, material and energy, digesting them into useful products and excreting waste. Industrial metabolism can be applied at many different levels: globally, nationally, regionally, by industry, by company and by site. Industrial metabolism analysis highlights the dramatic difference between natural and industrial metabolic processes. There are large differences between energy and material densities and fluxes and no primary producer (analogous to photosynthetic organisms) in the industrial world. In the natural world some nutrients flow in closed loops with near universal recycling, whereas industrial systems are mostly dissipative, leading to materials concentrations too low to be worth recovering but high enough to pollute. Currently industrial ecology goes further than industrial metabolism: it attempts to understand how the industrial system works as an interactive system, how it can be regulated, and how it interacts with the biosphere and other industrial systems (Johansson 2002).

The main sources of information about industrial ecology as a field of science are books by Ayres et al. (forthcoming in 2002), Graedel and Allenby (Graedel and Allenby 1995 and Allenby 1999) and Journal of Industrial Ecology (from 1997).

2.2 Current content, critics and future development

The current content and the main differences between different studies based on content analysis (modified from Indigo Development) and the interviews are presented in table 1.

O'Rourke et al. (1996) made the first critical review of the literature of industrial ecology and argued that: the field is poorly defined, the tools have methodological weaknesses, strategies do not often support the goals, implementation to date does not reflect the ideas expressed in literature and the technical analysis of energy issues and socio political analysis of means to transform industry are extremely limited.

Based on the critics presented by O'Rourke, three areas for development of the field were recently suggested (ISIE News 1/2002): the concepts of industrial ecology should be focused and refined, mechanisms for discussion and a debate involving a broad range of actors and interested parties should be created, and experiments with the implementation of the concepts should be carried out.

2.3 About the unique features of industrial ecology

2.3.1 Industrial ecology as a metaphor

Metaphors can extend our understanding by carrying our thoughts into unknown by using the known as a stepping stone, describe issues that are difficult to describe by using exact quantitative terms and be used to give new names for old activities.

It is at the moment not easy to see when a metaphor like industrial ecology used as a name of discipline actually adds insight and when it only conveys wishful thinking. It is not clear whether industrial ecology is only a descriptive name and tempting vision or can really be helpful in defining new strategies for industrial development (Johansson 2002).

2.3.2 Using models and lessons from ecology in design of industrial systems

Industrial ecology uses the concepts of ecology in a very selective way – most often only in a rhetorical manner. This is most probably so, because the field of industrial ecology is mainly developed by

Table 1. Current content of industrial ecology and main differences between the industrial ecology studies.

Current content	Main differences between the studies
Industrial ecology uses systems approach and the methods from systems sciences. Industrial ecology attempts to transform linear material and energy flows of industrial societies into cyclical material and energy flows by applying operation and function of natural ecosystems as a guidance and/or metaphor to find new ways of thinking. IE is (or should be) interdisciplinary, linking the research and planning of many fields.	What is the purpose of the study or activity: theoretical development, to describe a system, to give recommendations for changing systems or to implement something. What are the spatial and temporal boundaries of the system. Which elements are included/focus in the system: substances, materials, energy, products, plants, firms, industry sectors. What issues are taken into account: environmental, economical, social. What is the extent of change: Incremental changes in existing systems or far reaching transformations. What is or what are the sources of change/transformation: Institutional reforms, technological innovations, etc. And resulting from issues above: methods and tools (SFA, MFA, LCA, energy analysis, IOA) are different.

people who are more familiar with industrial systems. Industrial ecology has to great extent capitalized on the systems ecology model, which focuses on the flows of energy and nutrients at the ecosystem level. The reason is the attention given to production processes and their associated flows of energy and materials. It is suggested that application of the population ecology model to industrial systems (e.g. on products) could provide a useful complement to the systems ecology approach. The population ecology model emphasizes intra- and interspecies interactions of many types and studies population dynamics of the various species in ecosystem (Levine 1999).

Harte suggests two ways how business managers and policy makers can make use of the insights of ecology in design of industrial systems. One approach is to think of ecology as providing the blueprint and the second approach is to think of lessons from ecology as providing constraints or boundary conditions.

Harte argues that it does not make sense to treat ecosystems as blueprints. For example the carbon cycle is open and wasteful at any local scale and closed only at global scale. The extent it does make sense to recycle in industrial systems, it makes sense to do so as locally as possible. In ecology energy is used once and the waste is released to atmosphere. Thus human society as its makes use of waste heat is not using nature as a template. Natural ecological and evolutionary processes do not promote equity or justice. There is no external regulation, no regulatory body or forces that can protect the weak and unfortunate and create equity and justice.

On the other hand the ecology as a constraint is a very important lesson that is needed if the goal is sustainable society. Ecosystems are a source of essential services to society. The environmental footprint of human economy needs to be reduced so that natural ecosystem services can continue to be provided to society. The way to reduce the footprint is to reduce the consumption, population growth and protect habitat. A sustainable human future would not be the outcome of mimicking natural ecosystem processes. Instead a sustainable human future will require appropriate technology, wise planning and most importantly, preservation of natural ecosystems around the planet (Roundtable discussion 2001).

2.3.3 System level solutions

The most critical innovation of the industrial ecology model is claimed to be the level of inter-enterprise co-operation. It is suggested that industrial ecology will contribute to sustainable development as co-operation between various actors produces system innovations that go beyond process improvements or single product innovations (Wallner 1999, Huber 1998).

System innovations are distinguished from system improvement as being more comprehensive responses involving changes in production chains, in product-service systems and the way people consume and live. System innovations require the orientation of private and public actors towards long-term transition goals. By focusing on long term goals of sustainability and paying attention to dynamics and learning, the process of system innovation aims to overcome the conflict between long-term ambition and short-term concerns. System innovation involves changes in sociotechnical systems beyond a change in (technical) components. It is associated with new linkages, new knowledge, different rules and roles, a new logic of appropriateness and sometimes new organizations. System innovation usually consists of a combination of new and old components. Industrial ecology – defined as the closing of the material streams through the use of waste output of one company as a raw material by another company - is described as a special example of system innovation which combines old components in a novel way (Kemp and Rotmans 2001).

Eco-industrial networks (by-product synergy, integrative chain management, industrial symbiosis, eco-industrial parks) can be considered as an attempt to implement these ideas of industrial ecology in practice. The approach of using waste of one company as raw material of another is often criticized, because the major raw material and product flows are more or less excluded from observations and great effort is being made to minimise residuals (Wallner 1999).

Islands of sustainability and distributed economies are regional concepts that require tailor made solutions addressing all dimensions of sustainable development. The key questions are the interaction of global and local level and the economical feasibility of new local solutions.

2.4 Activities

Because of the relatively short history of the field of industrial ecology and its emerging nature it is difficult to list the organisations that have "industrial ecology" activities. Currently the activities in the field are mainly academic and scientific.

International Society of Industrial Ecology (ISIE) is a recently established society that promotes industrial ecology as a way of finding innovative solutions to complicated environmental problems. ISIE publishes ISIE newsletter and helds conferences. Academic and scientific organizations that have activities in the field of industrial ecology are for example International Institute of Applied Systems Analysis (IIASA), Wuppertal Institute for Climate, Environment and Energy/Material Flows and Structural Change, Chalmers University of Technology and Göteborg University/ Physical Resource Theory, International Institute for Industrial Environmental Economics at Lund University, Norwegian University of Science and Technology/Industrial Ecology Programme, Leiden University/ The Centre of Environmental Science, Erasmus University/ Centre for Sustainable Development and Management and Yale School of Forestry and Environmental Studies/ Industrial Environmental Management. There are also some consulting organizations that are mainly involved in developing eco-industrial networks in developing countries and North America.

In Finland the activities related to industrial ecology have been carried out in various research programmes financed mainly by the Ministry of Environment, the Ministry of Trade and Industry, the National Technology Agency and the Academy of Finland. Methodologies (for example life cycle analysis (LCA), material flow analysis (MFA) and input-output analysis (IOA)) of industrial ecology have been developed and used in several projects. Studies related to dematerialization have been carried out. Some regional systems have been studied as examples of industrial ecology. Also research and development related to utilization of municipal and industrial wastes and by- products and theoretical industrial ecology research has been carried out.

3 Case studies

The regional energy system of Jyväskylä can be regarded as an example of eco-industrial network although the ideas of industrial ecology and eco-industrial networks have not contributed to its formation. The aim of the study carried out together with partners in the network and University of Jyväskylä was to find out whether the environmental, economical and social performance of the current system was better compared with alternative choices that could have been done in the past.

The potential of e-commerce to reduce the greenhouse gas emissions related to food production-consumption system was analysed qualitatively for the whole demand-supply chain and quantitatively for the e-grocery home delivery service. The data for the quantitative study was produced in Tekes project Ecomlog (Supply Chain Solutions for Electronic Commerce) carried out by Helsinki University of Technology.

3.1 Regional energy system

In Jyväskylä, located in Central Finland and having a population of approx. 80 000, about 3300 GWh of primary energy per year is consumed. The largest proportion of the energy consumed in Jyväskylä is used for heating purposes. Heating of buildings accounts for nearly one half of the total energy consumption. Industrial processes account for 30% and road traffic about 10% (excluded in this study) of energy consumption. Industry is the biggest user of electricity in Jyväskylä, consuming about 40% of the total electricity consumed.

About 900 GWh/a of district heat is produced in the system, the main user being the City of Jyväskylä. The total process steam production of the sys-

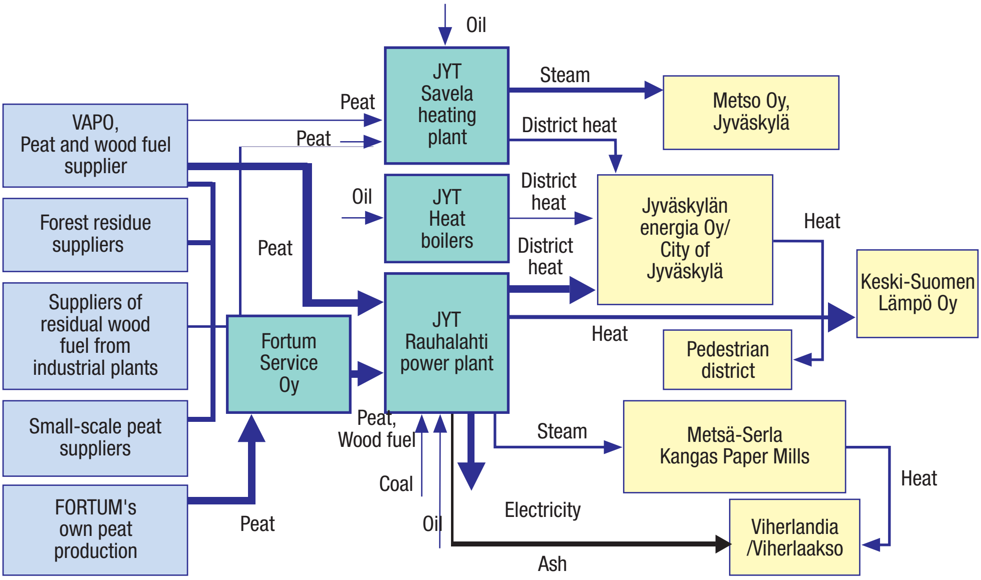

Figure 1. Regional energy supply system of the City of Jyväskylä.

tem is about 400 GWh/a and the electricity production about 400 GWh/a. CHP (Combined Heat and Power) production increases the overall efficiency to 80–90%, compared with 30–40% in conventional condensing power plants.

The heat for a cultivation, exhibition and sales center is extracted from the return steam condensate from Kangas Paper Mills. In addition, a pedestrian precinct in the Jyväskylä city center is kept clear of snow and ice in wintertime by using the district heat extracted from the district heating waters returning from the city.

Energy is mainly produced by using domestic, local fuels. The primary fuel is milled peat. In recent years, the use of wood residues from the neighbouring industrial plants has increased substantially. Recently a decision was made to invest in a fuel handling system that enables further increasing of the use of wood fuel.

A park and garden area situated near the power plant utilizes the ash produced by the power plant for landscaping. This saves thousands of tonnes of gravel that would otherwise be extracted from nature for these landscaping purposes. The utilization of ash from the nearby power plant reduces the need for transportation, which would be considerably higher if the gravel needed by the park and garden area were transported from further away. The need for transportation would also increase if the ash produced by the power plant had to be transported further to a disposal site.

In order to provide insight into the matter, the environmental, investment, employment and revenue (related to fuels used in energy production) effects generated by different technological and organizational choices made in the current energy system were compared with alternative systems. The amounts of heat, steam and electricity produced were assumed to be the same in all the systems.

The alternative systems are based on the following assumptions: there would be separate heating instead of district heating (fuel mix as today, as in 70’s and as in 60’s), there would be separate production of heat and electricity and all the actors would build their own power and/or heating plants.

The air emissions of the studied systems are shown in figure 2.

Table 2 summarizes the comparison of the current system with the alternative systems studied (a mi-

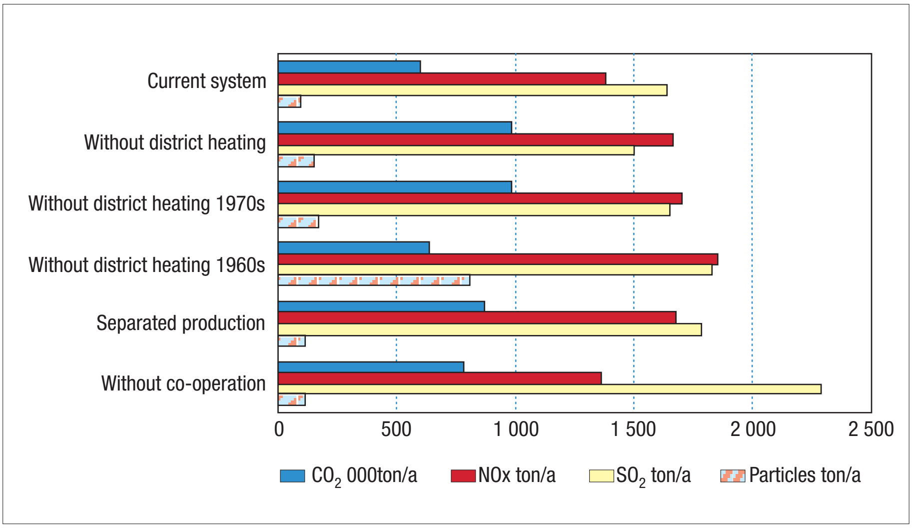

Figure 2. Air emissions in the current and alternative systems.

nus sign indicates higher emissions, lower employment, lower revenues for the region, and higher investment than in the current system, whereas a plus sign indicates the opposite).

The comparisons presented in table 2 show that the current energy system has a better environmental performance than have the alternative systems. The increase in the use of biomass in the current system will decrease CO_2 and SO_2 emissions significantly in the future. This indicates that the decisions made and the local co-operation have been beneficial for the environmental performance of energy generation in Jyväskylä.

The current system has also increased employment and the revenues for the region compared with the other alternative systems studied, except for the 1960s system, in which, because of the lower conversion efficiency, more biomass is used. The recent decision to invest in increasing the use of biomass will further increase the positive effect on

Table 2. Summary of the comparison of the current system with the alternative systems studied.

System/ Item	No district heating			Separated heat and power production	No co-operation	Increase of biomass in current system
	1960	1970	Current fuel mix			
CO_2 emissions	-	-	-	-	-	+
NO_x emissions	-	-	-	-	+	-
SO_2 emissions	-	-	+	-	-	+
Particle emissions	-	-	-	-	-	-
Employment	+	-	-	-	-	+
Revenues to region	+	-	-	-	-	+
Investments	-	+	+	-	-	-

employment and revenues for the region. The investments in the current system are lower than in the alternative systems, except in the systems where no district heating network is built and the individual heating boiler costs are moderate (Hämäläinen and Siikavirta 2001).

3.2 Food production and consumption system- e-grocery home delivery service

The case study revealed many possibilities for e-commerce to reduce GHG emissions in the food production and consumption system. Some potentially negative effects were also identified. It can be estimated that the current GHG emissions from grocery shopping travel are 1.1 Mt CO_2, which accounts for 1.4 percent of Finland's GHG emissions. Depending on the home delivery concept used, it is possible to reduce the GHG emissions by 18–87 percent from the situation in which households do the shopping trips by using their own cars. E-grocery home delivery service can thus lead to a GHG emission reduction of 0.19–0.95 Mt CO_2, which reduces emissions in Finland by roughly 0.3–1.3 percent.

The results indicate that the e-grocery home delivery service may have a significant potential to reduce GHG emissions from purchase shopping, depending on the selected operations model. The total GHG emission reduction potential of e-grocery home delivery service in Finland is, however, relatively small since transportation sector is responsible for only 15 percent of the GHG emissions.

Further study related to e-grocery home delivery service is required. More information is needed about the estimated theoretical potential of e-grocery home delivery service and the gap between the theoretical and likely potential. The narrowing of the gap between the theoretical and the actual potential requires a concept that will simultaneously provide added value to consumers and be profitable to companies. The concept showing the highest potential for reducing GHG emissions in this study was a service that provided the greatest flexibility in arranging efficient delivery making it attractive for the service provider. The customer should in this concept have a reception box and plan his/her shopping so that one delivery per week would suffice. The implementation of the concept requires significant changes in the shopping habits of customers and co-operation of a new kind between retailers and their customers.

There are also secondary effects that call for further study. E-commerce enables provision of environmental and social information and decisions based on it. The consumer could thus become able to influence and reduce the GHG emissions from the whole supply chain. On the other hand it is possible that money and time potentially saved by using e-grocery services is spent to substituting activivities that merely lead to higher GHG emissions (Siikavirta et al. 2001).

4 New perspectives on climate change research and greenhouse gas control from industrial ecology

4.1 Industrial ecology as a metaphor

Metaphor and analogy are close concepts. In the workshop, the possibility of studying industrial ecology as a double analogy was presented. It can be said that analogy is used in explanatory-predictive contexts, while metaphor can be used more broadly, in either explanatory-predictive or expressive-affective contexts.

Taking ecology as a base domain could provide new insights for framing and solving the environmental problems. Lessons from organising and management of the industrial systems could on the other hand bring new insights to management of the ecosystems (Hukkinen 2002).

It is at the moment not clear whether the use of industrial ecology as a metaphor, analogy or double analogy brings new insights into climate change research. The different ideas about the scope and definition of industrial ecology and mixed feelings about its usefulness that were revealed in the interviews and the workshop can be regarded as both a strength and a weakness in this respect.

4.2 Using natural systems in the design of the industrial systems

Closing the loops by using waste material of one industry or facility as a raw material of another is considered by many to be a central theme of industrial ecology. As the Jyväskylä case study shows, solutions of this type already are to some extent a normal practice in industry and have led to significant energy saving and greenhouse gas emission reductions. Some new ideas related to this theme and greenhouse gas control like utilization of CO_2 or wastes as raw material or energy have been studied in other Climtech projects.

Interesting themes for further studies could be the interaction of climate change related regulations and industrial ecosystems. What are their impacts in existing cases? Are they a driver or barrier for choosing and implementing the best future solutions from system level perspective in Finland or other countries?

Nature as provider of constraints and boundary conditions is a central theme in climate change research. There are huge efforts going on to understand climate change and its impacts better. If the goal of industrial ecology is to seek ways to redesign industrial systems to reduce their impact to levels natural system can sustain, it should study ways to reduce greenhouse gas emissions much more significantly than is done currently. It should also create an interdisciplinary framework enabling cooperation of a new kind between researchers studying climate change and its mitigation from different perspectives and different system levels and enhance the interaction between the producers and users of research results.

4.3 System level solutions

According to some opinions there is a need to study and find more radical system level innovations especially for challenging global problems like the climate change. Industrial ecology, on the other hand, is according to many a concept that is related to improvement of the existing industrial system and most suitable for studying regional systems. Radical innovations in industry may lead to increased efficiency and overcapacity. From regional perspective this may lead to lost jobs or complete lost industries.

Potentially a fruitful direction for the regional approach in the industrial ecology would be to study and experiment with islands of sustainability or distributed economies type of concepts. In these concepts, the guiding principle of the development of the system is sustainable development or well-being in broader sense. The effect of these concepts on greenhouse gas emissions is probably mostly indirect and difficult to quantify.

Industrial ecology could contribute to the transformation of the industrial systems by focusing on the actors and the rules that guide their behaviour. The studies should find out why the systems have developed as they have and how they can be changed. Knowing the history and lessons from discontinuities are important. The discussions in the workshop emphasized the importance of changes in the production cost structure and markets as drivers of change from the perspective of industry. The anticipated future development of the price of CO_2 will have a huge impact in this respect. The timeframe should be long enough, if the goal is to study more radical innovations. More attention should be paid on political and institutional barriers and issues, like capital, that are crucial for the implementation of the solutions.

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