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LONG-TERM INTEGRATION OF PHOTOVOLTAICS INTO THE GLOBAL ENERGY SYSTEM

10. November 1996

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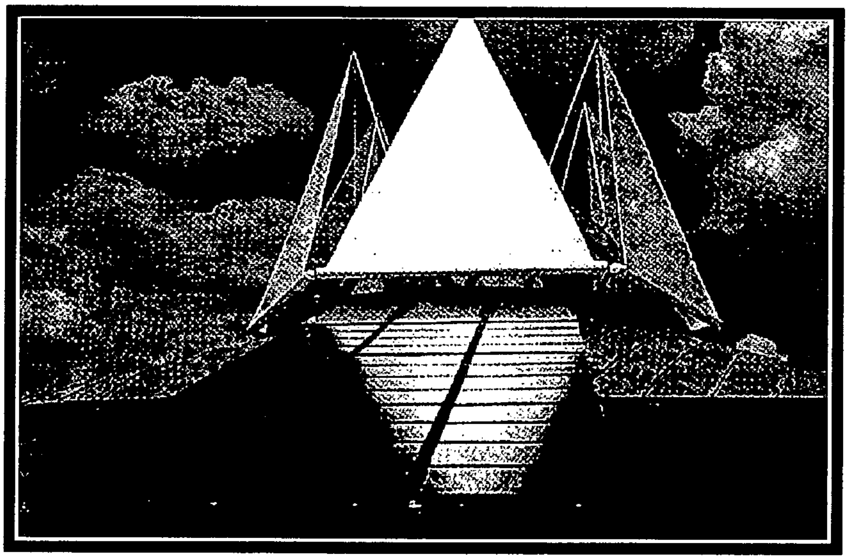

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LONG-TERM INTEGRATION OF PHOTOVOLTAICS INTO THE GLOBAL ENERGY SYSTEM
by Bent Sørensen
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Abstract

The paper discusses the role of photovoltaics in current energy scenario work on a local, regional and global scale, for the mid 21st century.

Cover illustration: Villa Vision, experimental house with solar cells, energy efficiency measures and non-polluting waste water trreatment and bulding materials, erected 1994 at Tåstrup by the Danish Technology Institute.

Long-Term Scenarios for the Integration of Photovoltaics into the Global Energy System

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Abstract

The paper discusses the role of photovoltaics in current energy scenario work on a local, regional or global scale, for the mid-21st century.

1. Introduction

A number of recent or ongoing projects deal with planning options for energy efficiency and renewable energy supply, in Europe [1-3] and globally [4,5]. The study presented here specifically looks at the role of photovoltaics in such scenarios for the future.

Two types of scenarios are considered. One is a fair market scenario, which assumes that price distortions in the energy field are eliminated by including environmental and other externalities in the prices of different energy forms. The other is an ecologically sustainable scenario, that in principle may be continued indefinitely with no resource depletion or increase in environmental impacts. In both types of scenarios renewable energy sources may become primary sources of energy, and substantial amounts of photovoltaic power would be expected to be incorporated into such scenarios for a future dated so far ahead, that the expected lowering of PV production costs makes this technology meet the costs of conventional energy sources, augmented with social externality costs.

2. Brief description of scenarios used

Four scenarios proposed recently will be analysed in terms of their expectations for PV. Their key features are as follows:

2.1. Ecologically sustainable scenario
This scenario assumes on normative grounds, that future energy provisions will be based on a system that does not cause depletion of resources or irreversible alteration of our environment. The scenario was first constructed for the country of Denmark (and named the "dark green scenario" of the Technology Council Study [3]). The scenario requires Denmark to be selfsufficient in energy, and energy trade with neighbouring countries is not considered. The largest components are wind power and gaseous and liquid fuels derived from the large Danish agricultural sector, but also some solar heat and building-integrated PV are considered. The intermittency of the wind and solar inputs is dealt with by extensive use of reversible fuel cells and fuel stores, such that the backup is both from biofuels and from gas produced during periods of

high solar or wind power production and stored in underground caverns (for which several Danish locations are favourable). Substantial effort is made to lower energy demand by energy efficiency measures. The scenario for the year 2030 is depicted in Figure 1.

2.2. The fair market scenario

This is a scenario for the mid 21st century for the current 15 European Union countries [6], based on the assumption that market forces will introduce renewable energy, if the social costs of fossil and nuclear energy are considered (global warming, accidents, etc. [7,8]). These costs may be directly reflected in prices (by an environmental tax) or may be incorporated only in the decision processes. Photovoltaics is assumed to play an increasingly large role as one goes towards the Southern part of Europe, and in addition to building-integrated units, there are central installations on marginal land, e.g. in Spain, as well as energy trade with Middle Eastern and North African countries, replacing their current oil exports with a smaller volume of solar electricity export. Also wind and biomass are important ingredients in the scenarios, with varying shares in different countries, depending on resource estimates. Again, greatly improved energy efficiency is believed to be economical if the marked prices include externalities (this is the meaning of the term "fair" market). Figure 2 shows the overall European energy scenario for the year 2050, with Figure 5 showing the transition in energy supply. The penetration of PV in each country is given in Table 1.

2.3 Decentralized renewable energy scenario

This is similar to the sustainable scenario but assumes a decentralized development of activities in society, which in terms of preferred energy systems means building-integrated PV and dispersed wind turbines, but no central solar receivers or large wind parks. The scenario is a global one, for which the regional distribution of sources is under investigation. The challenge associated with the decentralized paradigm is to determine a mix of locally available energy sources that will fulfill demand while minimizing energy trade (not eliminate it, as there will still be transmission grids interconnecting countries and regions, e.g. for electricity). The draft summary of the 2050 scenario is depicted in Figure 3 [5].

2.4. Centralized renewable energy scenario

This global scenario differs from the previous by allowing centralized PV installations in solar-favoured regions and thus more trade and transmission. Thereby it becomes possible to diminish the use of biomass in the energy sector, which is seen as a response to the quest for a sustainable agricultural practice, where agricultural land is not degraded or polluted by pesticides. The draft scenario summary is presented in Figure 4 [5]. The assumption of a 1 kW/cap. demand for the two global scenarios is fulfilled by combining a near full satisfaction of primary and secondary needs in all parts of the world with a high conversion efficiency from production through conversion all the way to the end-use.

3. PV penetration

Table 1 lists the penetrations of PV technology assumed in each scenario, and for the European scenario for each country. A calculation of potential production on suitably oriented rooftops and building facades was made on the basis of detailed building statistics in Denmark and Germany. In one region of Germany, the orientation and shade effects were assessed in further detail, and the results extrapolated to other regions of Europe on the basis of population density [9]. The fraction of the calculated potential actually used in the scenarios varies from 10 to 78%, as indicated in Table 1. The smallest penetrations are for high-latitude areas, while the largest penetrations are in sunny and clear regions. The values quoted for these regions, although smaller than the building-based potential, in practice include stand-alone systems. The installed collector area is given relative to the total land surface, as well as to population. Further, Table 1 gives the production per m^2 of collector, as an indication of the solar regime, as well as per capita. The system efficiency by 2050 is assumed to be 15%. As illustrated in Figure 6, penetration is high in suitably located areas with high building density, but also in sunny areas with much marginal land (e.g. Spain and Greece), despite a lower population density. Finally, Table 1 gives the fraction of the total scenario production of electricity, that is derived from PV. For the European scenarios, this fraction is low except for the Mediterranean countries, while for the global scenarios, it is considerably higher. This reflects that a large portion of world population lives in areas with high levels of solar radiation, and that other renewable sources such as wind are less prominent in these regions than in European coastal areas.

4. Conclusions

It is seen that many in the current generation of "greenhouse warming mitigation" scenarios place faith in the photovoltaic development. Of course, there are other scenarios emphasizing safe nuclear or clean fossil solutions [5]. The interesting common feature is, that expectations of rational energy use makes it possible to choose renewable energy scenarios with a very high share of PV, without encountering serious constraints from land use. In fact, even the most ambitious PV scenarios can be accommodated using only part of the building-based potential surface area.

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Figure captions

Figure 1. Scenario for an ecologically sustainable Danish energy system for year 2030 (units PJ/y) [3].

Figure 2. The fair market 2050 scenario for the 15 members of the European Union (units Twh/y) [6].

Figure 3. Global 2050 scenario based on renewable energy used in a decentralized fashion (units GWy/y) [5].

Figure 4. Global 2050 scenario based on renewable energy including centralized facilities (units GWy/y) [5].

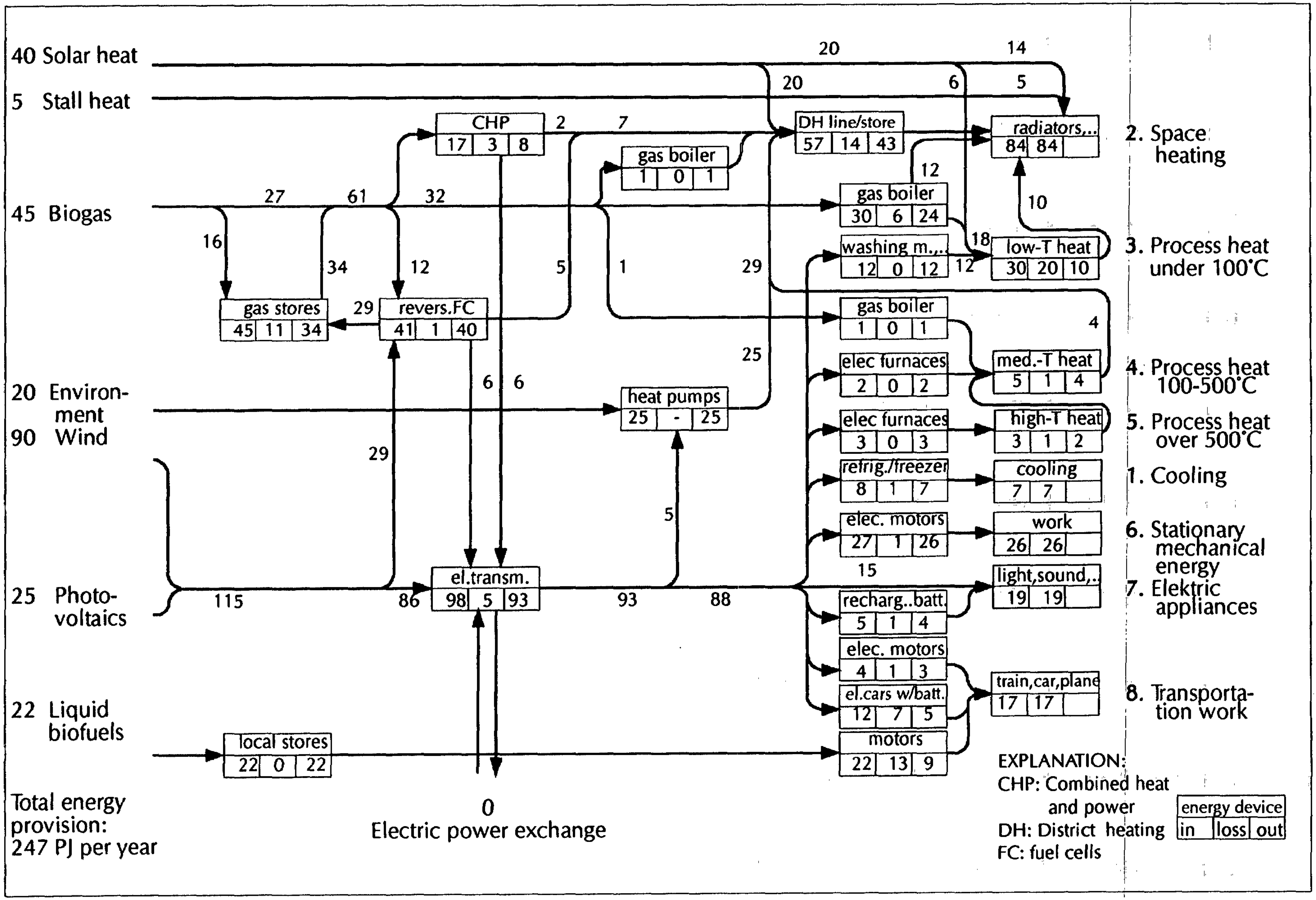
Figure 5. The primary energy supply in the European Union fair market scenario (units W/cap) [6].

Figure 6. Average PV power production (W/cap.) and installed PV capacity (m^2/km^2 of land) in all the scenarios.

Table caption

Table 1. Installed power production and average PV power production in scenarios.

Figure 1. Scenario for a renewable energy based system for Denmark anno 2030 (units: PJ per year). (Sørensen et al., 1994)



Fair market scenario for the energy system of the European Union (15 members) in 2050.

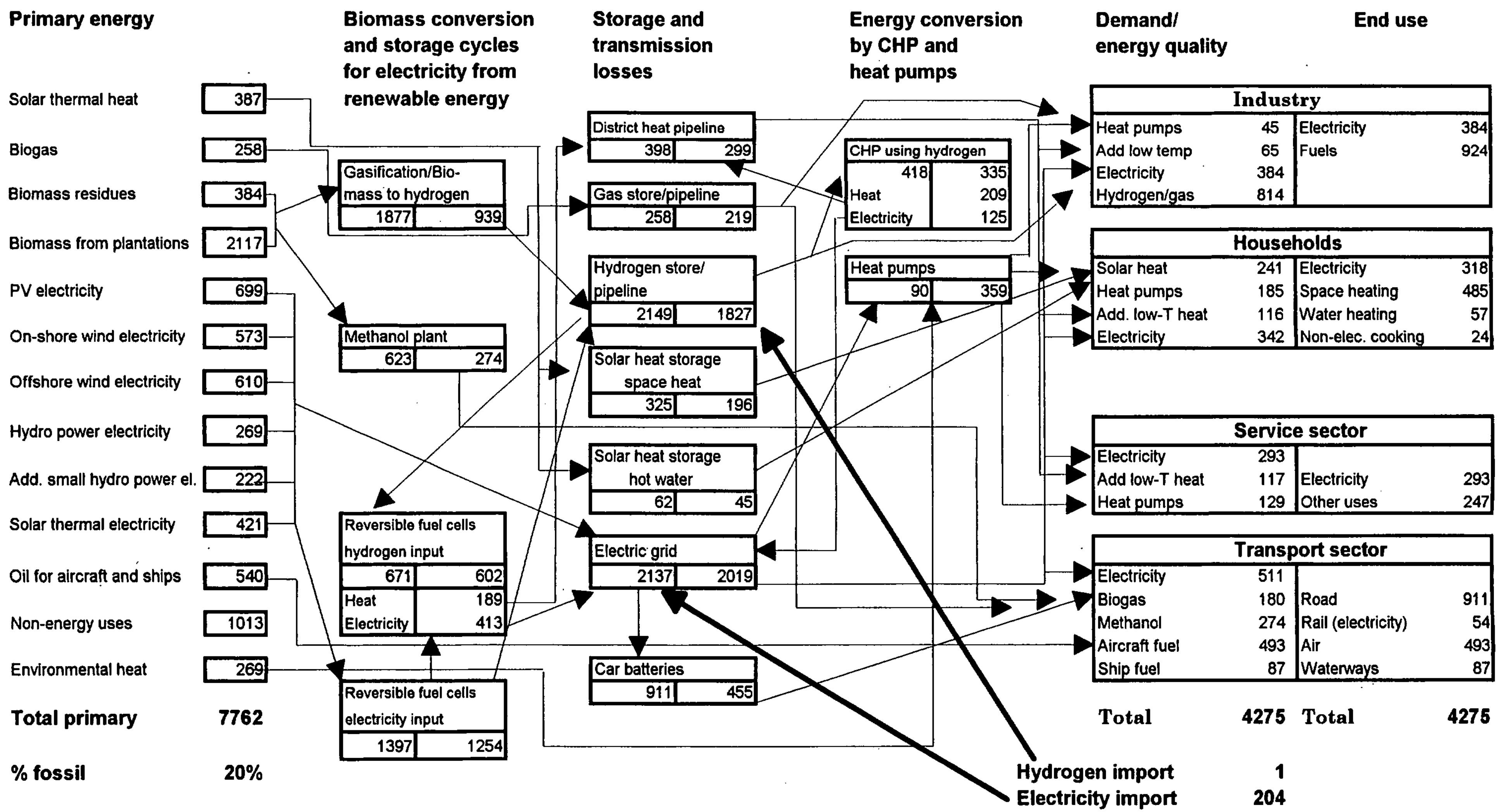


Figure 2

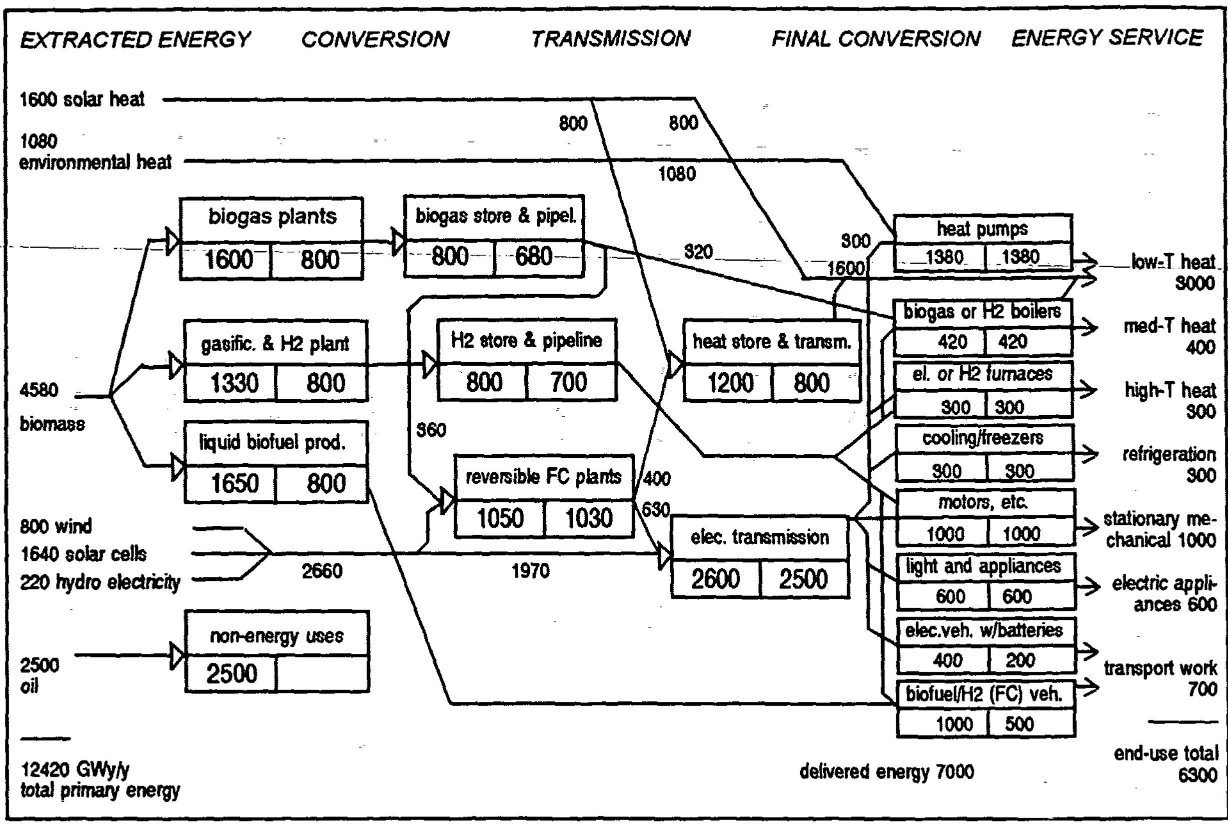


Figure 3. A global 2050 decentralized renewable energy scenario (GWy/y).

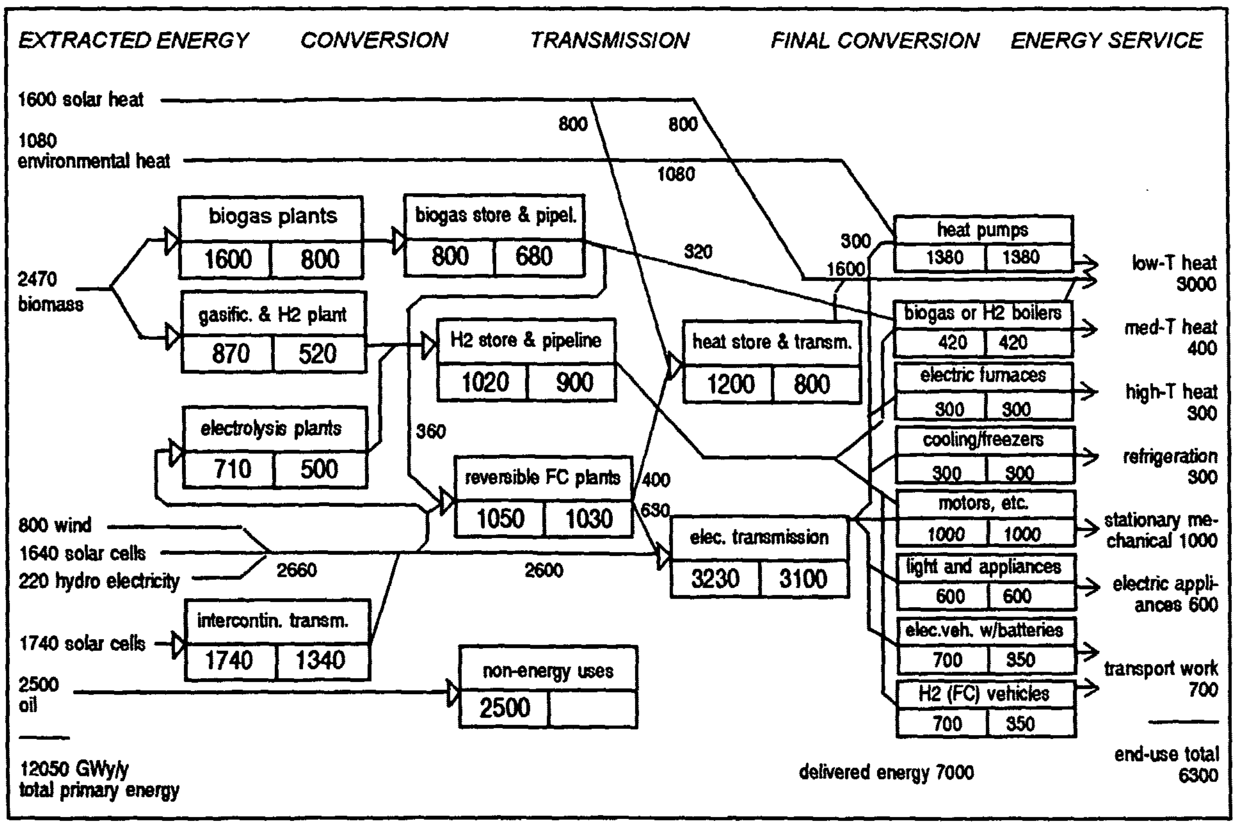
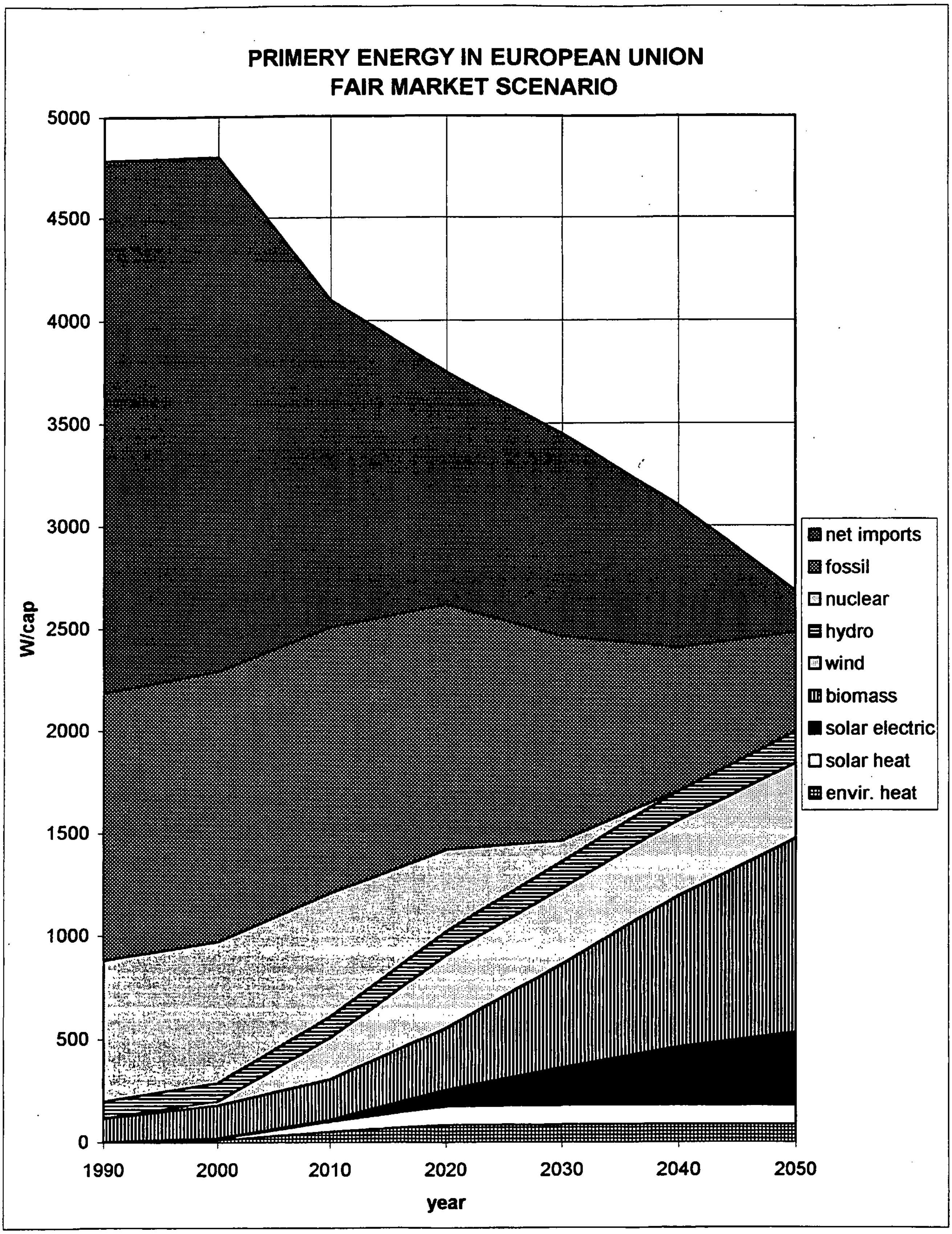


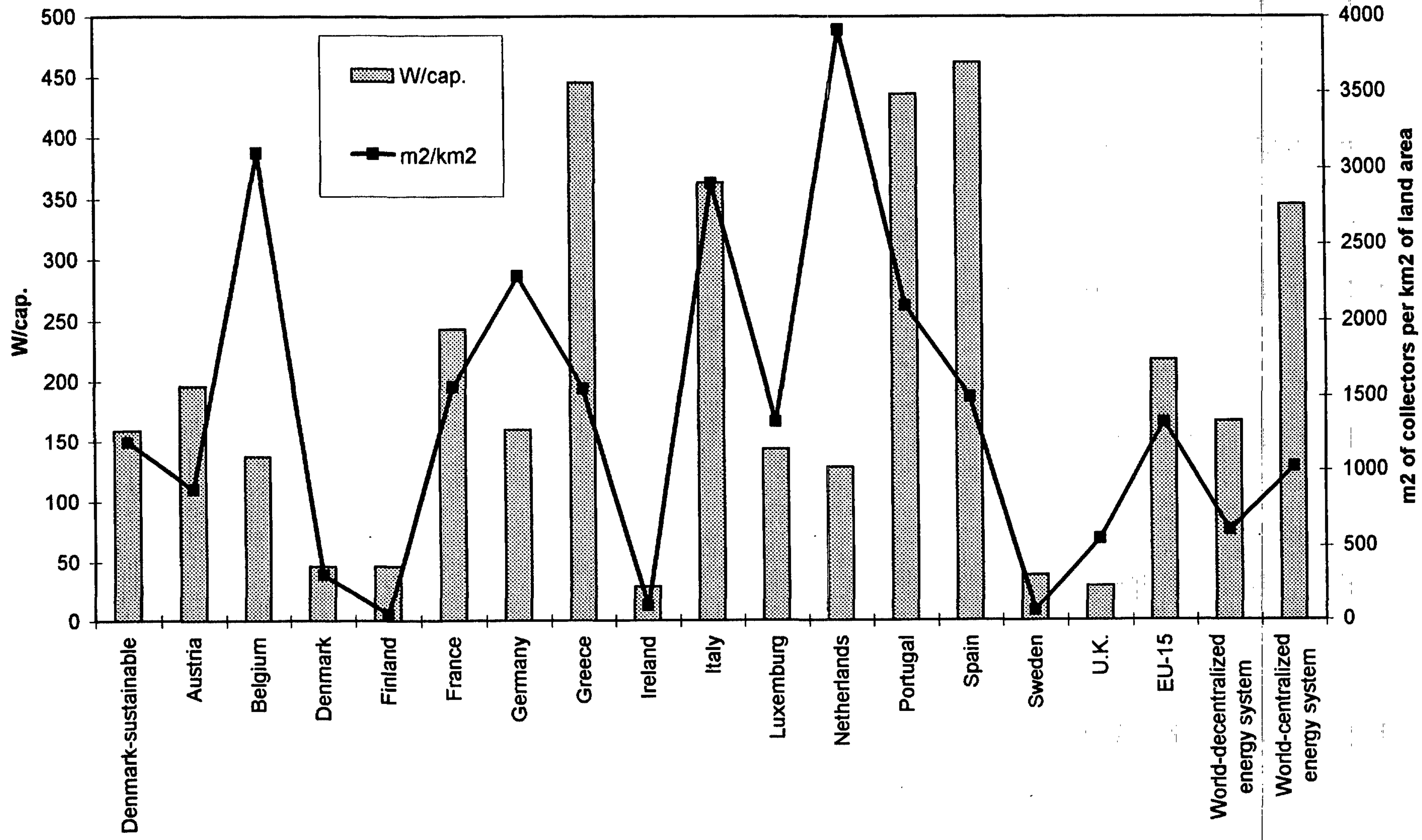
Figure 4. A global 2050 centralized renewable energy scenario (GWy/y).



PRIMERY ENERGY IN EUROPEAN UNION
FAIR MARKET SCENARIO
5000
4500
4000
3500
3000
2500
2000
1500
1000
500
0
W/cap
1990
2000
2010
2020
2030
2040
2050
year
net imports
fossil
nuclear
hydro
wind
biomass
solar electric
solar heat
envir. heat

Figure 5

AVERAGE POWER PRODUCTION IN SCENARIOS



Fair market scenario unless otherwise labelled

Figure 6

Scenario name-year	Ref.	Country	Installed PV power rel. to total land area/population/area of suitable roofs/facades			Average PV power production per area of collectors/ rel. to population/total electricity prod.		
			m2/km2	m2/cap.	%	W/m2	W/cap.	%
ESS-2030	3	Denmark	1190	10	38	16	159	21
FMS-2050	6	Austria	880	10	40	19	196	26
FMS-2050	6	Belgium	3100	9	40	15	137	18
FMS-2050	6	Denmark	310	3	10	16	46	2
FMS-2050	6	Finland	43	3	10	16	46	3
FMS-2050	6	France	1564	14	75	18	243	34
FMS-2050	6	Germany	2292	11	40	15	160	24
FMS-2050	6	Greece	1550	20	75	22	445	49
FMS-2050	6	Ireland	101	2	10	17	29	2
FMS-2050	6	Italy	2901	17	75	21	363	59
FMS-2050	6	Luxemburg	1333	10	40	15	143	6
FMS-2050	6	Netherlands	3912	8	40	15	128	20
FMS-2050	6	Portugal	2098	18	75	25	436	81
FMS-2050	6	Spain	1497	19	75	24	462	50
FMS-2050	6	Sweden	66	3	10	13	38	2
FMS-2050	6	U.K.	550	2	10	14	29	4
FMS-2050	6	EU-15	1325	11	47	19	217	33
DRE-2050	5	World	606	9	46	18	167	61
CRE-2050	5	World	1024	16	78	22	345	84

Table 1

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291/95 1st Annual Report from the project
LIFE-CYCLE ANALYSIS OF THE TOTAL DANISH ENERGY SYSTEM

an example of using methods developed for the OECD/IEA and the US/EU fuel cycle externality study

by: Bent Sørensen

292/95 Fotovoltaisk Statusnotat 3

af: Bent Sørensen

293/95 Geometridiskussionen - hvor blev den af?

af: Lotte Ludvigsen & Jens Frandsen

Vejleder: Anders Madsen

294/95 Universets udvidelse - et metaprojekt

Af: Jesper Duelund og Birthe Friis

Vejleder: Ib Lundgaard Rasmussen

295/95 A Review of Mathematical Modeling of the Controled Cardiovascular System

By: Johnny T. Ottesen

296/95 RETIKULER den klassiske mekanik

af: Peder Voetmann Christiansen

297/95 A fluid-dynamical model of the aorta with bifurcations

by: Mette Olufsen and Johnny Ottesen

298/95 Mordet på Schrödingers kat - et metaprojekt om to fortolkninger af kvantemekanikken

af: Maria Hermannsson, Sebastian Horst, Christina Specht

Vejledere: Jeppe Dyre og Peder Voetmann Christiansen

299/95 ADAM under figenbladet - et kig på en samfunds-videnskabelig matematisk model

Et matematisk modelprojekt

af: Claus Dræby, Michael Hansen, Tomas Højgård Jensen

Vejleder: Jørgen Larsen

300/95 Scenarios for Greenhouse Warming Mitigation

by: Bent Sørensen

301/95 TOK Modellering af træers vækst under påvirkning af ozon

af: Glenn Møller-Holst, Marina Johannessen, Birthe Nielsen og Bettina Sørensen

Vejleder: Jesper Larsen

302/95 KOMPRESSORER - Analyse af en matematisk model for aksialkompressorer

Projektrapport sf: Stine Bøggild, Jakob Hilmer, Pernille Postgaard

Vejleder: Viggo Andreasen

303/95 Masterlignings-modeller af Glasovergangen
Termisk-Mekanisk Relaksation
Specialerapport udarbejdet af:

Johannes K. Nielsen, Klaus Dahl Jensen

Vejledere: Jeppe C. Dyre, Jørgen Larsen

304a/95 STATISTIKNOTER Simple binomialfordelingsmodeller

af: Jørgen Larsen

304b/95 STATISTIKNOTER Simple normalfordelingsmodeller

af: Jørgen Larsen

304c/95 STATISTIKNOTER Simple Poissonfordelingsmodeller

af: Jørgen Larsen

304d/95 STATISTIKNOTER Simple multinomialfordelingsmodeller

af: Jørgen Larsen

304e/95 STATISTIKNOTER Mindre matematisk-statistisk opslagsværk indeholdende bl.a. ordforklaringer, resuméer og tabeller

af: Jørgen Larsen

305/95 The Maslov Index:
A Functional Analytical Definition
And The Spectral Flow Formula

By: B. Booss-Bavnbek, K. Furutani

306/95 Goals of mathematics teaching

Preprint of a chapter for the forth-
comming International Handbook of
Mathematics Education (Alan J.Bishop, ed)

By: Mogens Niss

307/95 Habit Formation and the Thirdness of Signs

Presented at the semiotic symposium

The Emergence of Codes and Intensions as
a Basis of Sign Processes

By: Peder Voetmann Christiansen

308/95 Metaforer i Fysikken

af: Marianne Wilcken Bjerregaard,
Frederik Voetmann Christiansen,
Jørn Skov Hansen, Klaus Dahl Jensen
Ole Schmidt

Vejledere: Peder Voetmann Christiansen og
Petr Viscor

309/95 Tiden og Tanken
En undersøgelse af begrebsverdenen Matematik
udført ved hjælp af en analogi med tid

af: Anita Stark og Randi Petersen

Vejleder: Bernhelm Booss-Bavnbek

310/96 Kursusmateriale til "Lineære strukturer fra
algebra og analyse" (E1)

af: Mogens Brun Heefelt

311/96 2nd Annual Report from the project
LIFE-CYCLE ANALYSIS OF THE TOTAL DANISH
ENERGY SYSTEM

by: Hélène Connor-Lajambe, Bernd Kuemmel,
Stefan Krüger Nielsen, Bent Sørensen

312/96 Grassmannian and Chiral Anomaly

by: B. Booss-Bavnbek, K.P.Wojciechowski

313/96 THE IRREDUCIBILITY OF CHANCE AND
THE OPENNESS OF THE FUTURE
The Logical Function of Idealism in Peirce's
Philosophy of Nature

By: Helmut Pape, University of Hannover

314/96 Feedback Regulation of Mammalian
Cardiovascular System

By: Johnny T. Ottesen

315/96 a + b "Rejsen til tidens indre" - Udarbejdelse af
et manuskript til en fjernsynsudsendelse
+ manuskript

af: Gunhild Hune og Karina Goyle

Vejledere: Peder Voetmann Christiansen og
Bruno Ingemann

316/96 Plasmaoscillation i natriumklynger

Specialerapport af: Peter Meibom, Mikko Østergård

Vejledere: Jeppe Dyre & Jørn Borggreen

317/96 Poincaré og symplektiske algoritmer

af: Ulla Rasmussen

Vejleder: Anders Madsen

318/96 Modelling the Respiratory System

by: Tine Guldager Christiansen, Claus Dræby

Supervisors: Viggo Andreasen, Michael Danielsen

319/96 Externality Estimation of Greenhouse Warming
Impacts

by: Bent Sørensen

320/96 Grassmannian and Boundary Contribution to the
-Determinant

by: K.P.Wojciechowski et al.

321/96 Modelkompetencer - udvikling og afprøvning
af et begrebsapparat

Specialerapport af: Nina Skov Hansen,
Christine Iversen, Kristin Troels-Smith

Vejleder: Morten Blomhøj

322/96 OPGAVESAMLING
Bredde-Kursus i Fysik 1976 - 1996

323/96 Structure and Dynamics of Symmetric Diblock
Copolymers
PhD Thesis
by: Christine Maria Papadakis

324/96 Non-linearity of Baroreceptor Nerves

by: Johnny T. Ottesen

325/96 Retorik eller realitet ?
Anvendelser af matematik i det danske
Gymnasiums matematikundervisning i
perioden 1903 - 88

Specialerapport af Helle Pilemann

Vejleder: Mogens Niss

326/96 Bevisteori
Eksemplificeret ved Gentzens bevis for
konsistensen af teorien om de naturlige tal

af: Gitte Andersen, Lise Mariane Jeppesen,
Klaus Frovin Jørgensen, Ivar Peter Zeck

Vejledere: Bernhelm Booss-Bavnbek og
Stig Andur Pedersen

327/96 NON-LINEAR MODELLING OF INTEGRATED ENERGY
SUPPLY AND DEMAND MATCHING SYSTEMS

by: Bent Sørensen