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Description of the CEEH integrated "Energy-Environment-Health-Cost" modelling franework system

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Publication date:
2011

Document Version
Publisher's PDF, also known as Version of record

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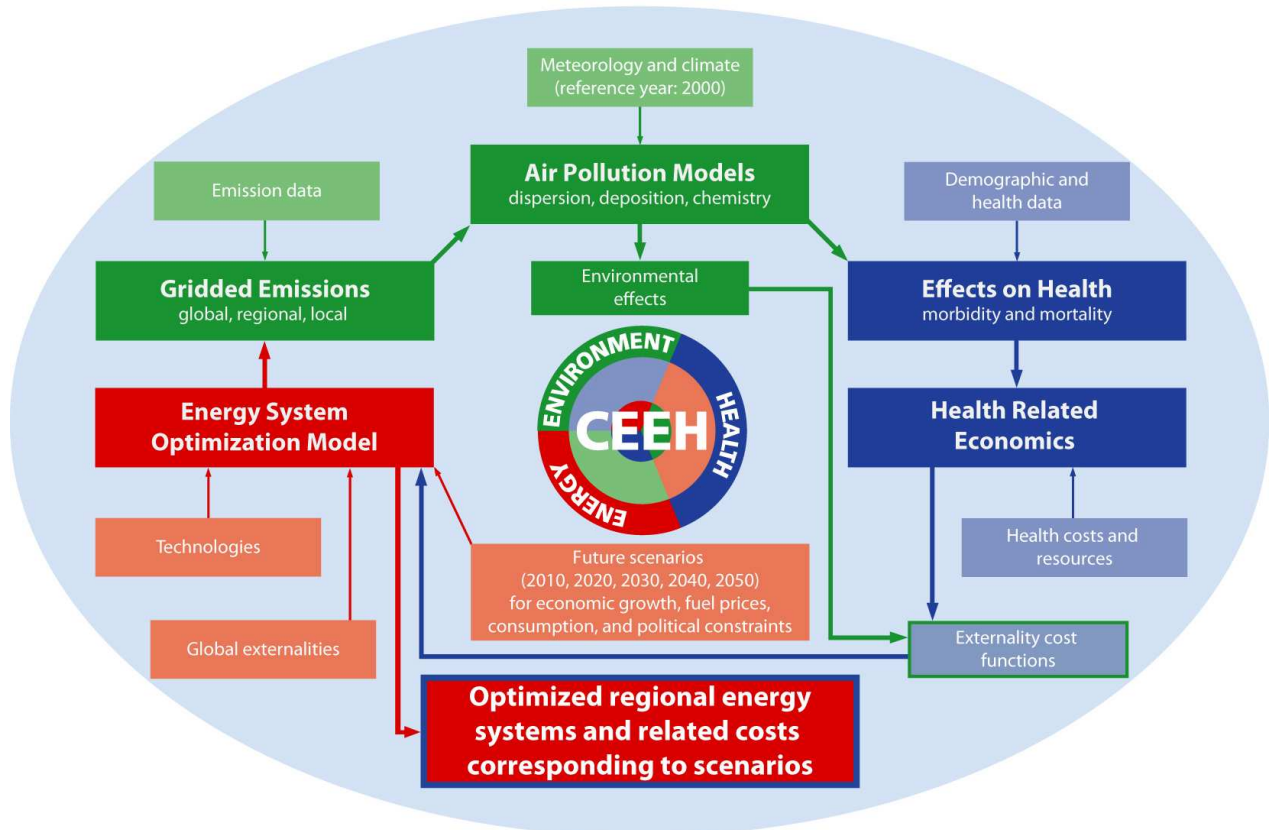
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Centre for
Energy, Environment and Health
Report series

CEEH Scientific Report No 1: Interrim Version 2011-01-20

Description of the CEEH integrated 'Energy-Environment-Health-Cost' modelling framework system

Centre for Energy, Environment and Health

Copenhagen 2011

Colophon

Serial title:
Centre for Energy, Environment and Health Report series

Title:
Description of the CEEH integrated 'Energy-Environment-Health-Cost' modelling framework system

Sub title:
CEEH Scientific Report No. 1

Editors: Alexander Baklanov, Eigil Kaas

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Language:
English

Content:

Summary

The purpose of this report is to present the general CEEH methodology with descriptions of individual models and components used in the CEEH model framework and definition of data exchange between the models/modules.

The Centre for Energy, Environment and Health (CEEH) model framework system simulates air pollution from energy production and consumption and its damaging impact on human health and the environment, and finally includes the external costs of damage in economic optimizations of future Danish energy systems. The modelling system is based on a number of individual models and data sets. Each model requires a different type of input data, to perform its part of the simulations.

The CEEH model system consists of:

- An energy optimization model, Balmorel, which finds the cheapest investment pattern to accomplish the futures demand for energy capacity.

- Atmospheric Chemical Transport (ACT) models, simulating atmospheric dispersion and chemical transformations of air pollution.

- Health effect and cost models, modelling the health impacts of a given air pollution scenario and long term effects of death rates on demography, and modelling the unit cost of a health case.

The first phase of CEEH's work has been to adjust the models performances and output formats to fit into the CEEH model system:

- An energy technology catalogue including air pollution emissions has been made. The catalogue is based on the energy catalogue from the Danish energy agency.

- Balmorel has been extended to include externality costs in energy system optimization, and will further be extended to include more sectors than power generation, e.g. road traffic, and a domestic heat saving option.

- The ACT's have been improved to work with higher spatial resolution and better performance of numerical schemes.

- In order to select air pollution species and types of health damages a thorough literature study has been done. Relevant concentration – response functions has been determined.

- A new health effect and cost model is under construction. This model differs markedly from previous long term health cost models in that it takes demographic development into consideration.

A demonstration phase CEEH system combining Balmorel and the externality costs from the EVA (Economic Valuation of Air Pollution) system has been set up. Hereby it has been possible to test the integrated approach used in CEEH. This EVA line system, as a by-product, estimated the health costs related to pollution from all different Danish sectors (also non-CEEH sectors such as ship traffic and agriculture).

Resumé

Formålet med denne rapport er en præsentation af CEEH metodologier med beskrivelse af de enkelte modeltyper, der anvendes i CEEH modelsystemet og definitioner af dataudvekslingen mellem de forskellige modeller og moduler.

Center for Energi, Miljø og Sundhed (CEEH) modelsystemet simulerer atmosfærisk spredning af luftforureningen fra energiproduktion og forbrænding og dens skadelige påvirkninger på menneskers sundhed og på miljøet. De eksterne omkostninger til samfundet ved disse påvirkninger beregnes og indregnes i økonomiske optimeringer af fremtidige danske energisystem. Model beregningerne er baseret på en række individuelle modeller og data sæt, der kræver forskellige typer af input til at udføre deres del af simuleringerne.

CEEH modelsystemet består af:

- En-energi-optimerings-model, Balmorel, som finder der mest fordelagtige investerings mønstre, der imødekommer fremtidens efterspørgsel efter energikapacitet.

- Atmosfærisk-kemiske transportmodeller (ACT), der simulerer atmosfærisk spredning og kemiske omdannelser af luftforurening.

- Sundheds-effekt- og omkostnings-modeller, der beregner sundhedskonsekvenser i den danske befolkning (og befolkningen i omkringliggende lande) for et givent forureningsscenarie, samt langtidseffekter i befolkningstal, grundet ændret levealder.

Første fase af CEEH's arbejde har bestået i at tilpasse modellerne og deres output til CEEH's modelsystem:

- Et energiteknologikatalog, der inkluderer luftforureningsemissioner er blevet udarbejdet. Kataloget er baseret på energistyrelsens energikatalog fra 2010.

- Balmorel er blevet udvidet til at inkludere eksterne omkostninger i energisystem optimeringerne, og vil blive udvidet til at inkludere flere sektorer end kraftværkerne (f.eks. trafik sektoren), samt et modul, der inkluderer investering i varmebesparelser i private boliger.

- ACT modellerne er blevet forbedret med højere rumlig opløsning og bedre numeriske skemaer.

- Koncentration–respons funktioner for helbredseffekter af relevante luft-forurenings-komponenter er blevet bestemt på baggrund af et omfattende litteratur studie.

- En ny avanceret sundheds-effekt- og omkostnings-model er ved at blive udviklet. Modellen tager blandt andet demografisk udvikling med i betragtning.

En test-optimering hvor eksternalitets-omkostninger var regnet med blev udført med Balmorel. Beregninger af sundhedseksternaliteter fra forskellige danske sektorer blev testet med EVA-systemet (Economic Valuation of Airpollution), som er et integreret modelsystem, der anvendes i CEEH.

Introduction

The connection between air pollution, originating from the burning of fossil fuels, and human health has been well established for several years. More people succumb every year to particle pollution from cars than from traffic accidents (Watkiss et al., 2005). Public concern about the consequences of air pollution on health, rising oil prices and the climatic impact of fossil fuel combustion, has encouraged politicians and the media to address energy type issues more frequently. This has convinced many to view the emergence of new environmentally friendly methods for energy production (bio fuel, hydrogen cells, etc.) with great optimism.

In the complicated network of health consequences, economical repercussions and climatic impacts, connections are dubious, but still economical dispositions are paramount, on both a private and a national level. Our common future is best safeguarded if these dispositions are made on a sound basis. Indeed, the purpose of the Danish strategic research Centre of Energy, Environment and Health (CEEH) is to develop such a decision support system. This is best done in the context of a unified interdisciplinary research effort, which can clarify the connections between the future energy production in Denmark, environment and health, and optimise these with respect to economy. In order to achieve such aims multidisciplinary experts from meteorology, environmental and health science, energy and economy are working closely together in the frame of the Centre which comprises the University of Copenhagen (UoC), the Danish Meteorological Institute (DMI), the National Environmental Research Institute, Aarhus University (NERI-AU), the Risø National Laboratory (Risø-DTU), the National Institute of Public Health (NIPH), the University of Southern Denmark (SDU) and Aarhus University (AU). The main goals of the Centre, which are all highly strategic for the Danish society, are:

(i) to study the future production of energy in Denmark and consequences of different scenarios with respect to airborne pollution and related impact on the environment and human health, and

(ii) to optimize the type of energy production and consumption with respect to economy including direct costs as well as indirect costs – externalities – related to environment and health.

The CEEH goals are achieved within the following six scientific work packages (WPs):

WP1: Baseline energy system modelling and emission scenarios;

WP2: Modelling of the environmental impact of the energy production /consumption;

WP3: Health impact of air pollution - the link between epidemiology and toxicology;

WP4: Quantification of pollutants and climate on population health;

WP5: Minimization of risk/impact on environment/health and optimization of energy production/ consumption;

WP6: Recommended scenarios for Denmark.

This scientific report is a part of WP5 activities that integrate specific models, developed by the CEEH partners within WP1-WP4, into the CEEH integrated 'energy-environment-health-cost' modelling framework (system). The report provides an overview of the data, the models, and the CEEH methodologies.

Chapter 1. CEEH integrated 'energy-environment-health-cost' modelling framework

1.1. Methodology of integrated modelling

The combined problems of energy consumption and environmental protection in modern societies call for the need to develop new multi-disciplinary approaches and models considering the possible effects on human health and optimisation of the energy production/consumption and mitigation scenarios.

A large spectrum of different impacts and elements of the system has to be considered. These include the effects of air pollution on the natural and human environment, and the effects of climate change arising from the release of greenhouse gases. Following the previous international experience (e.g., ExternE, 1995) wherever possible we have to use the 'impact pathway' or 'damage function' approach to follow the analysis from identification of burdens (e.g. emissions) through to impact assessment and then valuation in monetary terms. This requires a detailed knowledge of the technological possibilities, pollutant dispersion, analysis of effects on human and environmental health, and economics.

It is a challenge to construct an optimal frame for integrated 'energy-environment-health' modelling. The key elements have to be

- an energy systems catalogue according to societal demands,
- emissions associated with the various technologies,
- related air pollution and atmospheric dispersions,
- estimates of human exposure and related health effects,
- economic valuation of health and environmental effects (so-called externality costs), and
- economic optimization, considering all costs of the energy systems under different assumptions about e.g. future energy demands.

The end product will be optimal future scenarios for the Nordic energy systems. The interconnections between the modules are presented in Figure 1.1 and described in more detail below. The Figure illustrates the main steps of the impact pathways applied to the consequences of pollutant emissions. Each step is analysed with detailed process models. The general idea is to put the above-mentioned elements into the chain and make iterations before we obtain converged optimal solutions for the future energy system of Denmark and the surrounding countries with minimal impact on human health and environment. These impacts are valued and minimised in monetary terms.

Traditionally two types of optimisations have been applied when modelling "air pollution – effects":

1. System analysis and optimisation with simplified air pollution models (came from the economics research community);

2. Optimisation within air pollution models with modern comprehensive environmental models but with simplified models of the considered system (came from the atmospheric environment research community).

Our task is to combine the two approaches.

The CEEH energy-system optimization follows a typical "bottom-up" approach that complies with the projected energy demand. Following the impact pathway, individual processes are modelled with highest possible accuracy and combined into the macroscopic output.

1.2. Brief overview of the CEEH model framework

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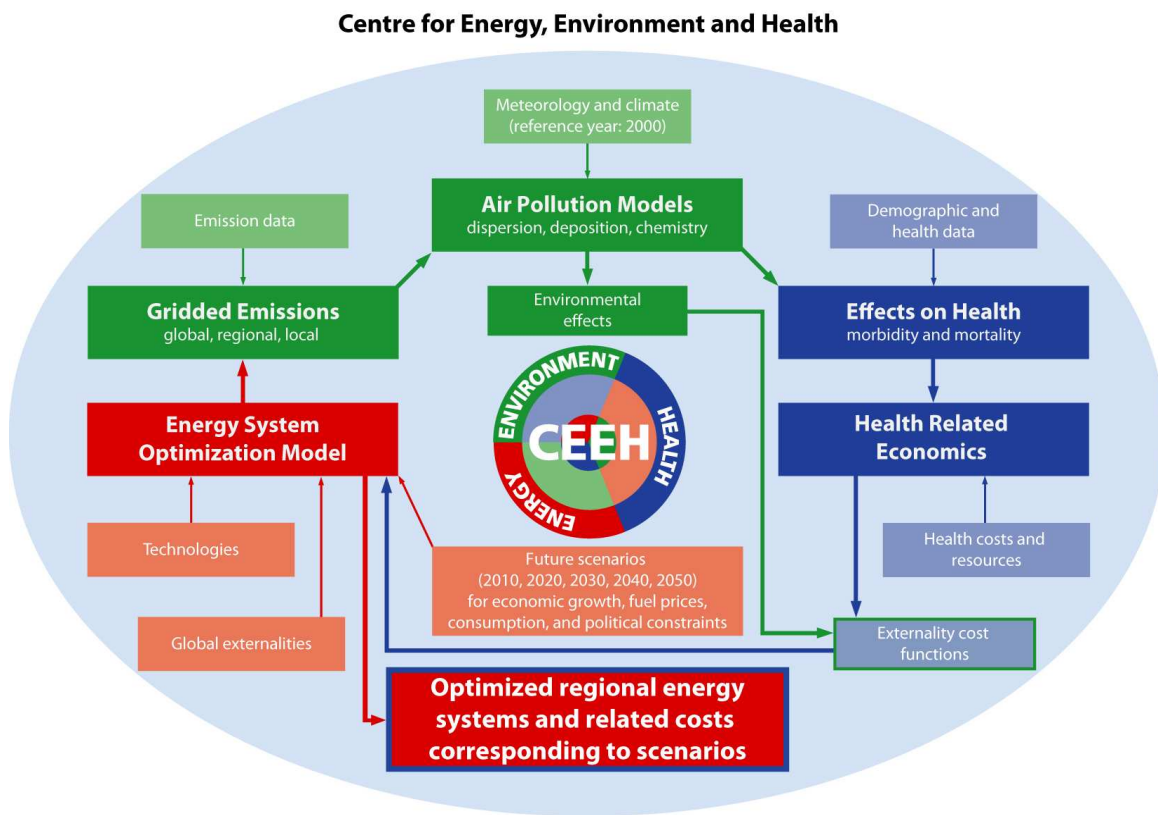
Figure 1.1 : Scheme of CEEH integrated modelling

The CEEH modelling framework system (Figure 1.1) is based on a number of individual models and data sets (strong coloured boxes) requiring different types of input (light coloured boxes). The energy system optimisation model (left red box) identifies, i.e. invests in, economically optimal energy systems. The unique feature of CEEH is that not only the direct costs but also indirect health and environment costs, so called externalities are taken into account in the optimization. Since power is traded freely on international markets ("Nord Pool Spot" and "Elbas") and since the Nordic countries and Germany are

interconnected via power lines the energy optimization is made as realistic as possible by including the entire Nordic region and northern Germany. In its final version it is planned that the energy optimization model can invest differently in each of the five Danish regions. In addition to the optimal energy investment patterns in each of the countries included, the optimisation model outputs emissions of pollutants related to each type of energy source/conversion. This information is combined on a geographical grid with general background emission inventories (left green box) and is given to atmospheric chemical transport models covering the Northern Hemisphere and in greater detail the European domain and Denmark (upper green box). The air pollution models, in turn, are outputting concentrations and depositions of a large number of health-affecting pollutants several times daily on a fine geographical grid. This means that the excess local exposure of airborne pollutants due to CEEH-domain emissions can be quantified. Based on physiological air pollution studies and studies of large population cohorts (upper blue box) it is then possible to quantify mortality and morbidity as well as related costs (lower blue box). These costs are finally added to environmental costs (smaller green box), resulting in total costs due to "traditional" air-pollution (lower right box). This externality and that associated with global climate costs (lower left box) are provided to the energy optimization model. In this way the total externality cost associated with the invested system is obtained. In practise the whole CEEH model chain must be run a few times to minimise the cost and optimise the final system.

The product from CEEH will be an energy production and consumption modelling system available for public use. This system is applicable for decision and policy making with respect to present and future conditions, including climate, weather and air quality related impacts on human health. Furthermore, Danish private companies can use the future energy scenarios as guidelines for long-term investments in development of new energy systems.

The CEEH optimizations will be performed for several scenarios reflecting different assumptions on demand and world economic growth determining fuel prices and on political constraints related mainly to the health system and to possible national or international goals and protocols. An example of the latter will be a scenario with zero CO_2 emissions associated with new investments. Furthermore, scenarios reflecting different demographic development will be used.

The aim of the very first air pollution investigations was to investigate possible differences between different available emission inventories (EMEP, MEGAPOLI etc). This was followed by simulations with ACTM's being driven by reference weather conditions defined as the actual weather hour by hour in year 2000, and with agreed present day background emission inventories, e.g. EMEP (European Monitoring and Evaluation Programme, http://www.ceip.at/, see details in Section 2.2). The externalities associated with these emissions were used in the so-called CEEH EVA line system. I.e. externalities have been estimated using the EVA system and these costs were provided to the energy optimization model.

ACTM simulations to be performed in 2011 for the CEEH optimizations in years 2020, 2030, 2040 and 2050 will use the EU thematic strategy emissions and IPCC RCP4.5 (Intergovernmental Panel on Climate Change, http://www.ipcc.ch/) scenario (Northern Hemisphere background emissions in CEEH) emissions.

In order to determine the marginal difference in regional ambient concentration levels different approaches are used in CEEH ACTMs. E.g., a tagging facility (Brandt et al., 2011) is build into the Danish Eulerian Model (DEHM) in order to calculate the delta-concentration directly. It is advisable to use tagging in the DEHM simulations because if the alternative method (two runs with and without a particular emission source correction and then subtracting the two runs annual results (= delta-concentrations)) is used the result can contain more numerical noise. For this problem the ACTM output/ delta-concentrations are very dependent on numerical methods (advection schemes, filters, solvers etc.). Thus, different numerical technique employed by Comprehensive Air quality Model with extensions (CAMx) makes it possible to use the alternative method mentioned above. The delta-concentrations are used to determine the exposure related to specific emission sources. For the local scale calculations are performed once with site-specific emissions only. The calculated delta-concentrations are multiplied grid cell by grid cell with the population data (number of inhabitants and age distribution) to obtain an estimate for the total annual accumulated exposure, which again gives the calculated response through a series of exposure-response functions specific for certain population groups and chemical components. Finally the economical valuation is performed by multiplying the result with the response-dependent monetary values.

Chapter 2. Description of the main models involved

2.1. Energy optimisation model

The backbone energy optimisation model in CEEH is the Nordic power and district heating market model – Balmorel (*Ravn, 2001*).

Balmorel is a linear optimisation model of a power and heat system with perfect competition. Based on assumptions for the development in input parameters such as fuel prices and technology data, the model calculates new investments in power plants and transmission lines and the operation of the units in the power system. The model is multi-regional consisting of regions connected by transmission lines. It takes into account the balance between supply including net export and demand in each region, capacity restrictions for production units and transmission lines, technical restrictions for CHP (Combined Heat and Power) plants, balance equations for heat, and hydropower. The health costs have been integrated in the objective function in order to take these into account in the optimisation process. Balmorel has been expanded and improved in several projects (all to be found on www.balmorel.com) and in CEEH focus has been on including more sectors in Balmorel, so it in principle covers all energy conversion and related emissions in the Danish energy system; and it includes power and district heat production in the surrounding countries. It is important to model all sectors to get the full picture of air pollution from Danish sources.
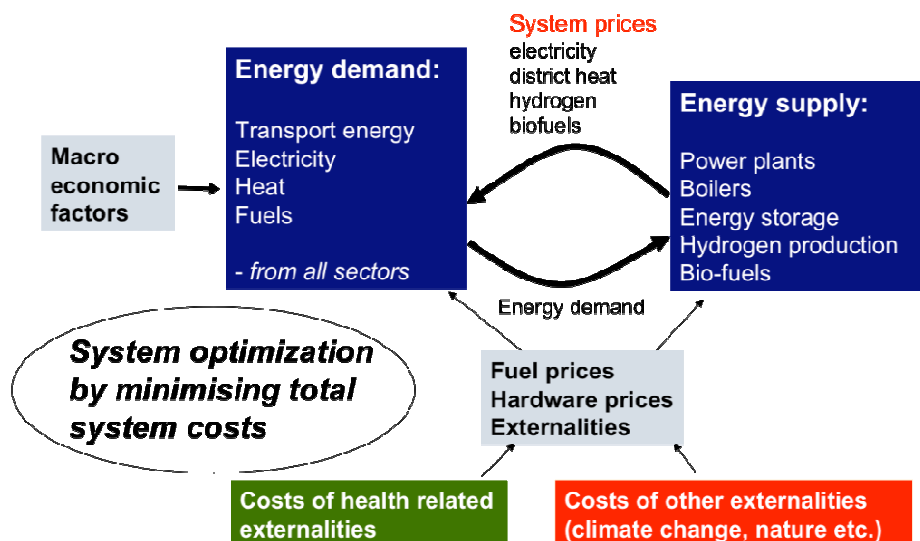

Figure 2.1 : Illustration of inputs to the energy system model.

A complete energy system model includes all sectors and Figure 2.1 illustrates how it in principle works. Exogenous to the energy system model is typical the growth in energy demand driven by economic

growth (macro-economic factors); prices on fuel and externalities. Internal in a model the energy demand can react on market prices on electricity and heat by investing in more efficient technologies or simply by turning down consumption. This reaction in demand is often not included in energy system models and in the CEEH Balmorel only a part of the demand side is included and only in terms of a possibility to invest in more efficient technologies. This is however still an improvement to the "normal" modelling of energy systems and throughout the CEEH projects more sectors and technologies will be included in Balmorel.

The sectors in the Danish energy system are schematically illustrated in Figure 2.2 and the dashed lines illustrate what is included in the CEEH Balmorel so far. So the power and heating system is fully included, individual boilers for heating houses are also included, while industrial boilers are not yet included. The transport sector is so far represented by an exogenous calculated demand for electricity, bio-fuels and hydrogen. The power and heat consumption for producing these fuels are then included in the energy demand.
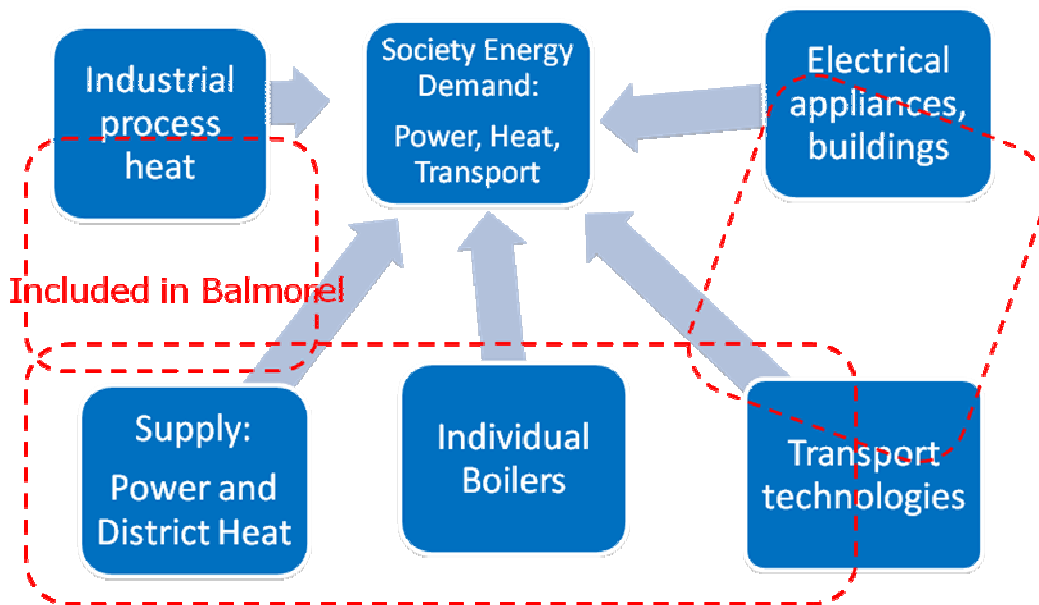
Figure 2.2: Sectors in the Danish energy system considered where the red dotted rectangles illustrates which parts presently represented by Balmorel.

An optimization model like Balmorel seeks the least cost solution for the system modeled and all trade-offs is handled on ideal functioning markets. The central square in Figure 2.2 ("Society energy demand") represents the market place where demand for electricity, heat and transport energy is cleared with the production of these products.

The modelling principle is the same for all sectors in Balmorel. In the starting year there is an existing stock of technologies and as they reach their technical lifetime or if new technology is cheaper to use, they will be replaced by possible technologies capable of delivering the same energy services. All these

technologies are collected in a database from which the model can choose. Looking at the power sector then there is a huge amount of power plants in the countries in the model. Figure 2.3 shows the existing installed capacity in Denmark, Norway, Sweden, Finland and Germany and as time goes by the power plants are demolished, only hydro power and waste incineration are assumed to live throughout the scenario period. All exiting thermal power plants are seen to be phased out before 2035.
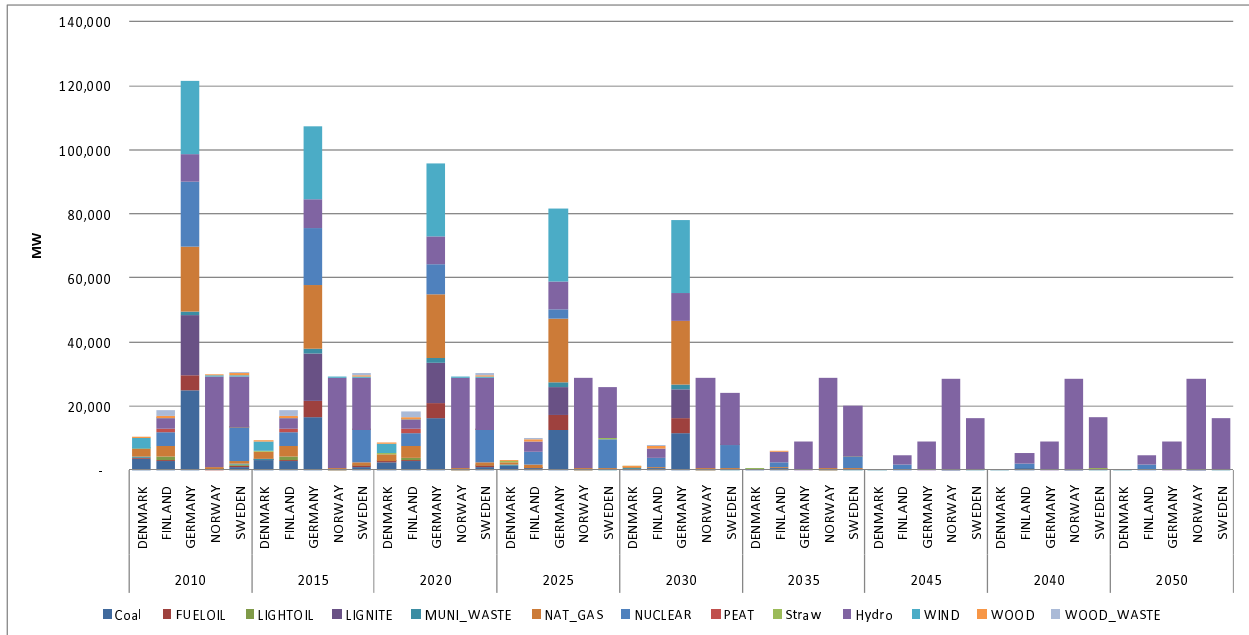
Figure 2.3: Capacity of existing power plants in Balmorel.

For replacement of the demolished power plants there is created a database with possible power producing units.

The work flow in Balmorel can be described in some steps combining the creation of long term scenarios with detailed checking of the energy system for critical years. In the following text this work flow is described in more details.

Optimal power system configurations in, e.g., 2050 can be derived by running the Balmorel model with endogenous investments for the period (2010-2050) using 5-year steps. The approach is illustrated in Figure 2.4.

The working flow in the analysis starts with the creation of a database with existing technologies (box 2) in the energy system (power plants, heating plants, heat storages etc.). Then scenario specific parameters are added to the database; those include demand predictions; future available technologies; fuel prices; and externalities (box 1).
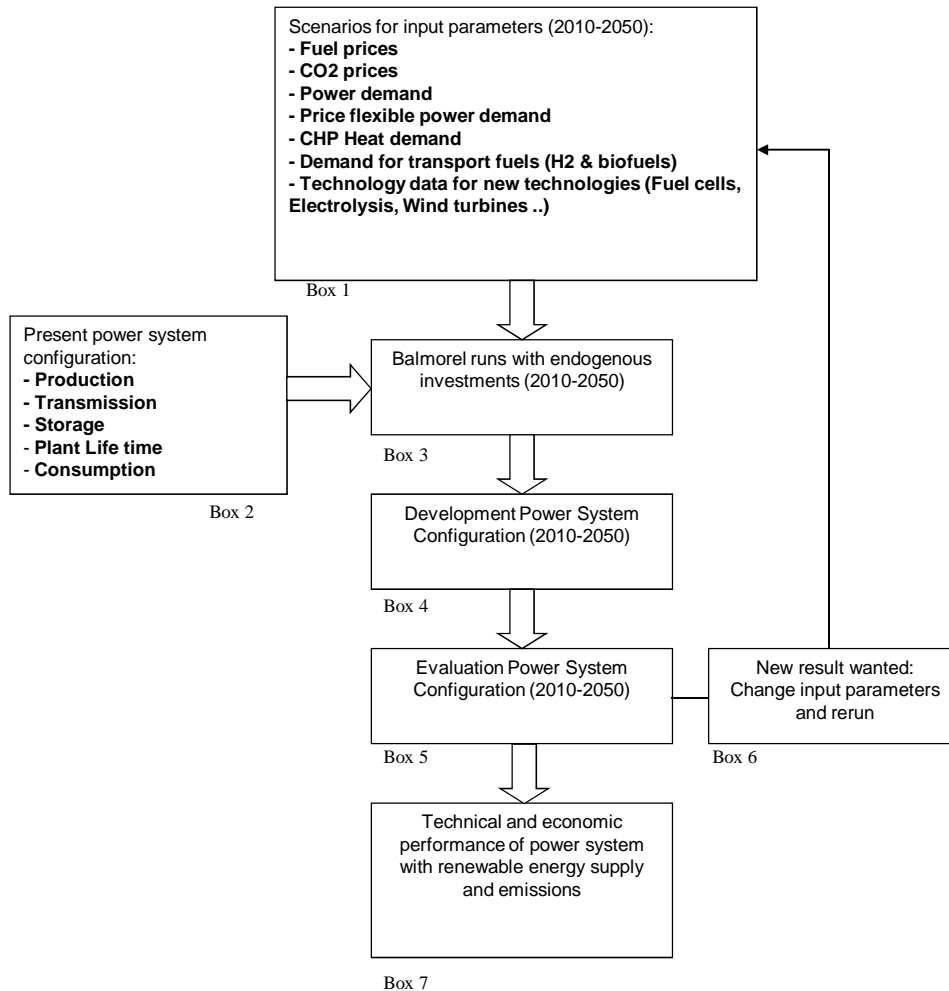
Figure 2.4: Overview of the methodology used for analyzing future investment paths.

For long term investment scenarios, Balmorel will typically run with a more aggregated time resolution than one hour, e.g., 5 periods within each of the 52 weeks in a year, adding up to 260 time-slices per year. Box 3 and 4 in Figure 2.4 represents model simulation with endogenous investments and output of modelling results in a result-database ready for inspection.

The evaluation of the resulting energy system is carried out by checking total economy for the scenario, power and heat production divided on technologies and fuel, production of hydrogen and environmental effects (box 5). If a certain goal for the future energy system is not fulfilled such as a target for installation of wind power or for CO_2-emission, then the input parameters are adjusted (box 6) and the model is run again.

Important is also whether the found energy system can function with a more detailed time resolution enabling better representation of load and wind power variability. To investigate this, the model can run on an hourly basis for a chosen year or for a period in a year. In this mode the model do not undertake

investments but uses the energy system found by running the model in the less detailed time resolution and then tests if there will be capacity shortage or power/heat surplus in some time-steps (box 5). If the system is not in balance in every time-step corrections in input parameters are necessary, e.g., the inclusion of more technologies which can solve the given problem or adding more restrictions on the investment in the different technologies, e.g., securing sufficient back-up capacity.

When the evaluation turns out successfully then the results from the scenario modelling describe a realistic proposal for an economic optimal energy system given the scenario specific input parameters (box 7).

As mentioned above the Balmorel model can run in two different modes:

1. BALYEAR: A model run with yearly optimization horizon, more aggregated time resolution than hourly and with endogenous investments.
2. BALHOUR: A model run with weekly optimization horizon, hourly time resolution and without endogenous investments.

The investments in production and transmission capacity generated by running BALYEAR can be transferred and used in BALHOUR. BALYEAR and BALHOUR share the same input data with the hourly time series used in BALHOUR being aggregated into the time resolution used in BALYEAR. The yearly optimization horizon used in BALYEAR is suitable when optimizing seasonal storage, such as determining the most optimal use of seasonal hydrogen storage. Running BALYEAR with 260 time steps corresponding to 52 weeks each sub divided into 5 time steps makes the transfer of results concerning the usage of seasonal storage from BALYEAR into BALHOUR relatively straight forward. For example the weekly use of hydropower calculated in BALYEAR is introduced in BALHOUR as a restriction specifying the weekly hydropower production in each week and region. BALHOUR can then determine how this weekly hydropower production is distributed on hours.

The presented Balmorel covers Denmark, Norway, Sweden, Finland and Germany. Each country is divided into several regions (except from Finland where there only is one region) in order to model the effect of the most important bottle necks in the Nordic transmission grid, see Figure 2.5.

Between regions the transmission lines have capacity constraints on the export and import of power from region to region. Electricity is balanced at a regional level including the effect of power transmission between regions. Each region is subdivided into areas. Areas are introduced to represent heating grids, e.g., to represent a district heating grid with a certain number of CHP plants and heat boilers and a certain time varying heat demand. Each production unit is allocated to an area. District heat demand and supply are balanced on area level, i.e., district heat is not traded between areas.
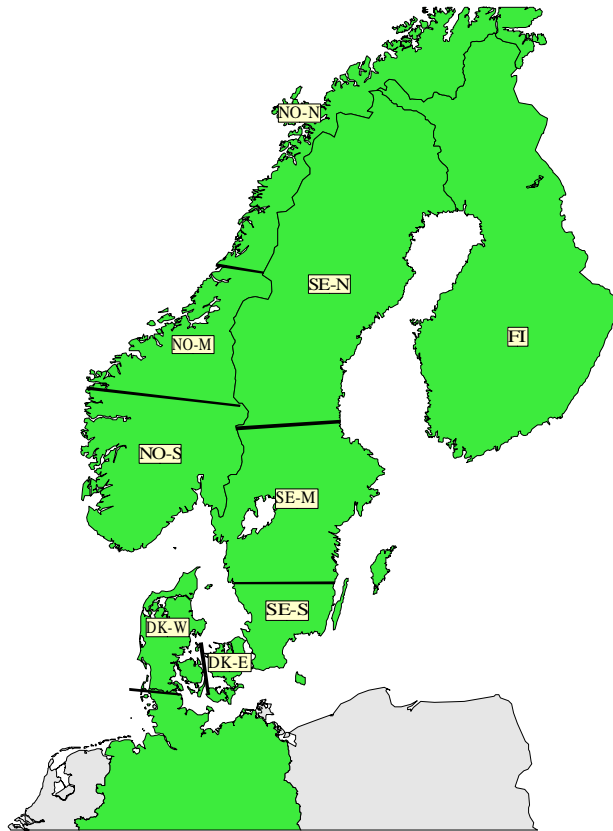
Figure 2.5: The sub-domains in the standard Balmorel modeling system for power and district heating.

The CEEH-version of the Balmorel modelling system has the following features:

- *Electricity and heat*
  The model operates with existing generation units based on the given power and heat demand and makes investments in new capacity in such a way that the resulting costs of the whole system are minimised. Generation technologies available to the model are CHP (Combined Heat and Power), extraction, condensing and back-pressure power plants, heat only units, and various renewable technologies (i.e. hydro, wind, and solar power).

- *Energy storage*
  As energy carriers and storage media all relevant technologies including hydrogen storage are considered. For stabilization of the heat and power system investments in heat pumps play a central role, which is very important for optimal investments in wind energy systems.

- *Heat savings module*
  This feature considers demand side measures, which can reduce the heat demand. The model has flexibility to choose whether to respond to heat demand simply by generating the necessary

amount of heat or to invest for instance in better insulating walls and windows reducing the demand and then generating the rest, whatever is cheaper.

- *Hydrogen*
  This part of the model enables utilisation of hydrogen-based technologies for electricity storage and transportation.

- *Accounting for externalities*
  This module allows one to take into account the cost of environmental and health damage from an energy system. The cost is attributed to emission of a particular substance from the energy system influencing both operation and investment decisions.

- *Transport*
  This module, taking into account the transport sector in the energy system optimisation model, is under development in CEEH. In a future world with much more weight on e.g. electric cars, hydrogen cars, or bio-fuelled cars, the car fleet may play an important role as energy storage improving the efficiency and utilization of wind power.

- *Emissions*
  This component outputs emissions of pollutants related to the actual Balmorel investments in the different sub-domains.

2.2. Emissions, scenarios and databases

As mentioned above Balmorel is outputting emissions associated with the invested energy systems in the different sub-domains. This can involve emissions from all known types of energy conversions. e.g. fossil fuels, nuclear power, solar and wind energy, and bio fuel. In the CEEH emissions module the emissions are combined with background (i.e. not part of the CEEH optimization) emission inventories from other sources and also from other regions in Europe and over the Northern Hemisphere (NH) according to the present day estimates and future scenarios (e.g., EMEP, IIASA, EDGAR, GEIA, IPCC, RETRO, and MEGAPOLI). The total NH emissions, with enhanced detail in Europe and over the CEEH region in particular, provide gridded input to the atmospheric chemistry transport models. These models, in turn, calculate concentrations and deposition rates of gases and aerosols as a function of space and time.

The atmospheric pollutants generated from the fuel cycles of the fossil fuels in power and CHP plants are predominantly emitted from the tall stacks of power plants. Therefore, we have concentrated on both primary emissions and pollutants associated with acidic deposition and photo oxidants arising from fuel combustion. Although other sources will arise from up- and downstream fuel cycle phases, including emissions from construction activities and fuel extraction, these sources are generally negligible when compared to fossil fuel power station emissions (*ExternE, 1995b*). The key health affecting pollutants in focus are described in Table 2.1 and include SO_2, O_3, NOx, CO, $PM_{2.5}$, PM_{10}, nitrate, sulphate, dioxin, PAH, Pb, Hg and some other metals.

Following the main goals of CEEH a number of background emission inventories describing the present and future energy and transport systems in Denmark will be simulated within the CEEH model framework for the period 2000 to 2050.

The aim of the first runs is to investigate disagreement between different available data sets, and to test how the models behave when changed to IPCC emissions (Intergovernmental Panel on Climate Change, http://www.ipcc.ch/). All the runs will be done using Numerical Weather Prediction (NWP) data for the reference year 2000 with EDGAR (Emission Database for Global Atmospheric Research, http://www.mnp.nl/edgar/) or GEIA (Global Emissions Inventory Activity, http://www.geiacenter.org/) plus EMEP (European Monitoring and Evaluation Programme, http://www.ceip.at/), IPCC + EMEP emission inventories and IPCC emission data alone. Then EU thematic strategy emissions and IPCC RCP4,5 scenario (background emissions in CEEH) will be used for comparison over Northern Hemisphere. The next step is calculation of new emissions for Denmark with Balmorel model (without/ with external costs); these model runs should cover all the scenario years. Then the exploration of the impact of different future scenarios will be done, one is repetition of the previous step but with different future emissions scenarios, to find the level of externalities with an alternative global economic development and thereby another level of emissions.
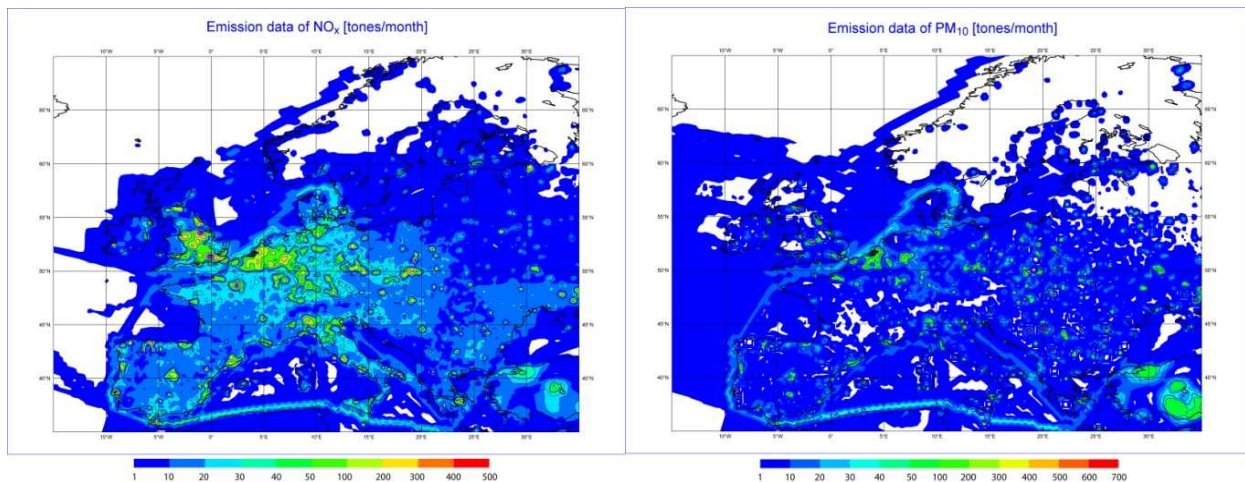
Figure 2.6: Example of NO_x (a) and PM_{10} (b) emission maps over Europe based on the EMEP emission inventory (tonnes/month) which is used in CEEH as background emissions (after extraction of Danish emissions).

When pollutants are emitted into the atmosphere (especially greenhouse gasses) they influence the radiation balance and chemical reactions in the atmosphere and thereby the meteorology/climate. On the other hand, climate change can also affect emissions of different pollutants, first of all biogenic emissions, dusting, etc. So the effect of including climate change in the models is also analyzed. The final step is focused on replacement of the cost functions used in the demonstration phase system (see section 4) by new ones developed within CEEH. These will be done based on the ACTM's runs for 2020, 2030, 2040 and 2050 with emissions from Balmorel with and without externalities.

One example of NO_x and PM_{10} emission maps over Europe based on the EMEP emission inventory (tonnes/month) which is used in CEEH as background emissions (after extraction of Danish emissions) presented in Figure 2.6. Information on specific scenarios, emission databases used in CEEH simulations, will be published in CEEH report no. 2 (*Karlsson et al., 2011*).

2.3. Atmospheric pollution models

To assess spatial and temporal distributions of pollutants and chemical species in the air and their deposition on the Earth's surface, dispersion and atmospheric chemical transport models (ACTMs) are used at different scales, addressing different applications from emergency preparedness, ecotoxicology, and air pollution effects on human health to global atmospheric chemical composition and climate change. Although ACT models differ in their treatment of different mechanisms and feedbacks, they all employ a similar framework and consist of the same major modules:

- Transport and diffusion - calculating three-dimensional motion of gases and aerosols in a gridded model domain;
- Gas-phase chemistry - calculating changes in gaseous concentrations due to chemical transformations;
- Aerosol - calculating size distribution and chemical composition of aerosols accounting for chemical and physical transformations;
- Cloud/fog meteorology - calculating physical characteristics of clouds and fog based on the information from the meteorological model;
- Cloud/fog chemistry - calculating changes in chemical concentrations in clouds/fog water;
- Wet deposition - calculating the rates of deposition due to precipitation (and, possibly, cloud impaction and fog settling) and the corresponding changes in chemical concentrations;
- Dry deposition - calculating the rates of dry deposition for gases and aerosols and the corresponding changes in their concentrations.

Depending on the scale of the considered domain and processes in focus in different CEEH studies we are using different ACTMs within the CEEH model framework. The following models are used for regional scale air pollution simulations:

- The **DEHM** (Danish Eulerian Hemispheric Model)

- The **Tropospheric Chemistry-Aerosol-Cloud Modelling System (~CAMx)**

- The **Enviro-HIRLAM** (HIgh Resolution Limited Area Model)

- The Danish Emergency Response Model of the Atmosphere (**DERMA**)

For urban or street scale air pollution simulations are used:

- The Urban Background Model (**UBM**)

- The Operational Street Pollution Model (**OSPM**)

- The **M2UE** (Micro-scale Model for Urban Environment)

Below a short description of the ACTMs used in our framework is given.

DEHM The DEHM (Danish Eulerian Hemispheric Model) is an Eulerian Atmospheric Chemical Transport Model (ACTM) system with two—way nesting capability to obtain high resolution over limited areas. This makes it easy to change the chemistry, apply the model to different emission inventories, meteorological data and run the model over other model domains. The model covers the majority of the Northern Hemisphere. The horizontal resolution in the mother domain is 150 km x 150 km. Each sub-domain has a grid resolution which is three times higher than the parent grid. The location of these sub-domains is flexible. In Figure 2.7 the model domains used in CEEH are presented. The vertical discretization is defined on an irregular grid with 20 layers up to ~18 km. The advection is solved numerically using an Accurate Space Derivatives scheme with non-periodic boundary conditions for the horizontal advection and a finite elements scheme for the vertical advection. The diffusion is solved using the finite elements scheme (For details regarding the numerical implementation and the model architecture, see *Christensen, 1997; Frohn et al., 2001; Frohn et al., 2002; Frohn, 2004*).

Three different atmospheric chemical mechanisms are currently included in DEHM:

- A regional chemical scheme based on the EMEP scheme with 58 chemical compounds, 9 particles, and 120 chemical reactions. The particulate matters are calculated as total $PM_{2.5}$, PM_{10} and TSP, including primary and secondary aerosols (NO_3, SO_4 and NH_4) as well as biomass burning and sea salt (*Frohn et al., 2002; Frohn et al., 2003*).

- A chemical scheme of Persistent Organic Pollutants (POPs) including α-HCH, γ-HCH, PCB28, PCB52, PCB101, PCB180 and D5 (*Hansen et al., 2004; Hansen et al., 2008a; Hansen et al., 2008b*).

- A mercury chemical scheme with 14 mercury species (*Christensen et al., 2004; Heidam et al., 2004; Skov et al., 2004*).

Due to the chemical behaviour of the POP and mercury scheme these two schemes have to be used together with the regional chemical scheme. The emissions are based on a combination of the GEIA, EDGAR, IPCC/RCP and the EMEP emissions as well as local emission inventories for Denmark. Finally, a tagging capability is build into DEHM, which makes it possible to calculate delta-concentrations from specific emission sources in the Eulerian model framework, a necessary facility in the type of model simulations that are performed in CEEH (*Brandt et al., 2011*).
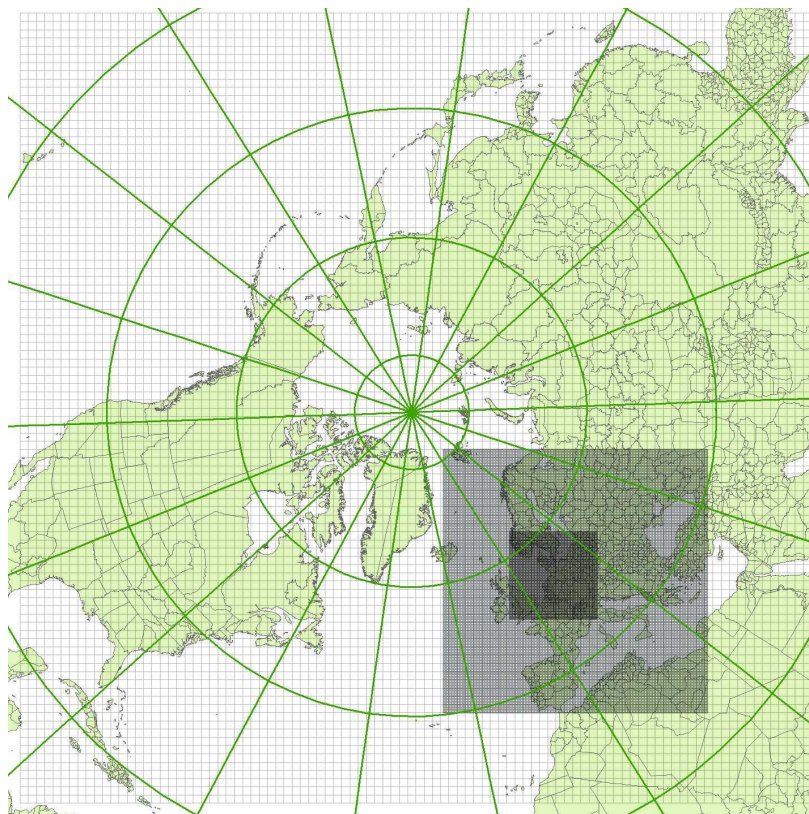
Figure 2.7 : The DEHM domain (polar stereographic projection) with a mother domain and two nests.

DEHM has been used in various applications over the years: operationally within the Danish Background Monitoring Programmes of Air Quality (*Ellermann et al., 2007*) and since 1999 as air pollution forecasting (*Brandt et al., 2001*), modelling of POPs (*Hansen et al., 2004; Hansen et al., 2008a; Hansen et al., 2008b*), modelling of mercury in the Arctic (Christensen et al., 2004; Heidam et al., 2004; Skov et al., 2004), and recently to scenario studies of the climatic change impact on air pollution levels (*Hedegaard et al., 2008*).

Tropospheric Chemistry-Aerosol-Cloud Modelling System

The Tropospheric Chemistry Aerosol Cloud modelling system is a highly flexible multi-module based system (Figure 2.8a). There are two versions of the system. The first one (*Gross and Baklanov 2004*) is a further development of the Lagrangian chemistry model MOON (*Gross et al. 2005; Madsen 2006*), where the chemistry aerosol cloud module concept makes it easy to perform chemical transformations, and apply with other emission inventories and/or meteorological datasets. Furthermore, the aerosol physics in the new module is more advanced. The second version is Eulerian and moreover, it is based originally on the CAMx model (http://www.camx.com). Two chemical schemes can be used: the Regional Acid Chemistry Mechanism (RACM) (*Stockwell et al., 1997*) and an updated version of Carbon

Bond IV (CB-IV) Mechanism (*Gery et al., 1989*) with improved isoprene chemistry. Both mechanisms are used together with the Tropospheric Ultraviolet and Visible radiation model (TUV) (*Madronich, 2002*) to calculate photolysis rate coefficients, and emissions from EMEP.

The aerosol module treats condensation, evaporation, nucleation, deposition and coagulation of aerosols (*Baklanov, 2002*) as shown in Figure 2.8a. The numerical evolution of aerosols is solved by treating the aerosol size distributions as log-normal distributions. However, the aerosol module as a part of the modelling system has not been routinely tested yet in the 3D version, i.e. only in 0D (see *Gross and Baklanov, 2004)*; although it was evaluated in the 3D Enviro-HIRLAM research version of the model (see *Korsholm et al., 2009*).

The horizontal and vertical resolutions of the model depend on a resolution of the meteorological and emission data. At present the model runs over a 0.2°×0.2° horizontal grid (Figure 2.8b), and it has a vertical resolution of 25 levels. These vertical levels cover the lowest 3 km of the troposphere. The amount of chemical compounds, which is transported from the free troposphere into the atmospheric boundary layer, is determined by the meteorological information and the concentration of the chemical compounds in the free troposphere. These concentrations depend on the longitude, latitude, land/sea and month (*Gross et al., 2005*). The advection is solved using the Bott scheme – an Eulerian mass flux based scheme.

The model system is developed to simulate aerosols and gas-phase compounds from regional to urban scale. It has been used for air quality forecasts of ground-level gas-phase air pollutants and modelling of historical data.
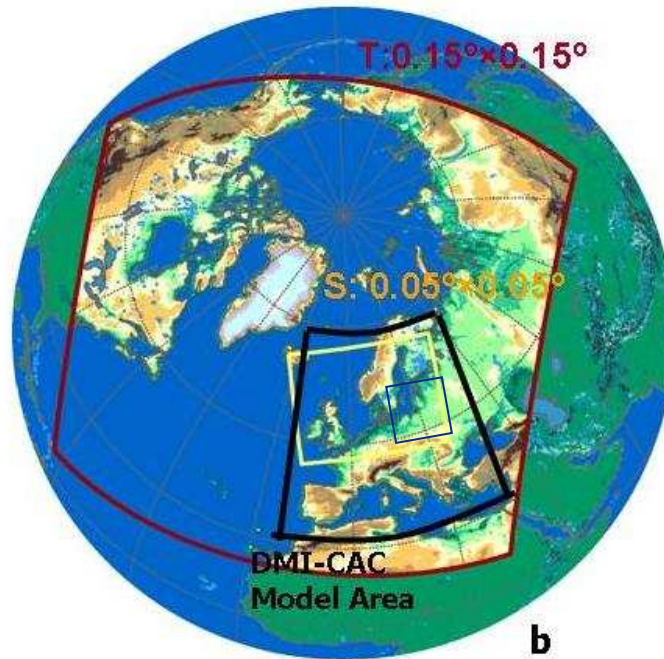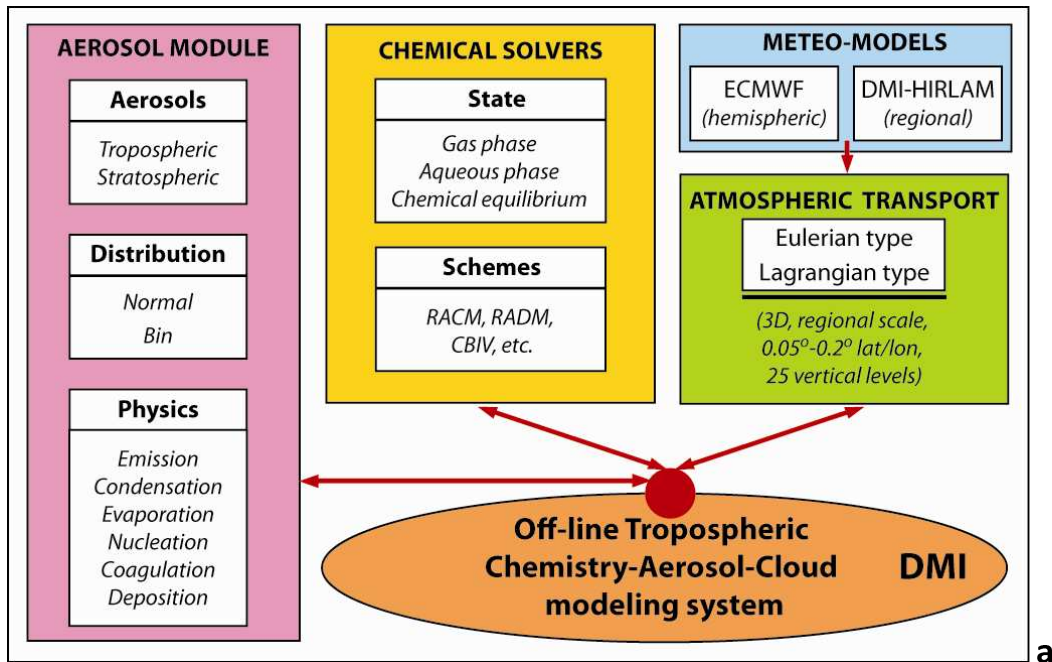
Figure 2.8 : (a) Schematic description of the Tropospheric Chemistry Aerosol Cloud modelling systems developed at DMI and (b) operational modelling areas.

Enviro-HIRLAM The Enviro-HIRLAM is a new generation online coupled numerical weather prediction (NWP) and ACT model for research and forecasting of both meteorological and chemical weather (Figure

2.9). The integrated modelling system is developed by DMI and other collaborators[1] (*Chenevez et al., 2004; Baklanov et al., 2004, 2008a; Korsholm et al., 2008a, Korsholm, 2009*) and included by the European HIRLAM consortium as the baseline system in the HIRLAM Chemical Branch (https://hirlam.org/trac/wiki), it is used in several countries.
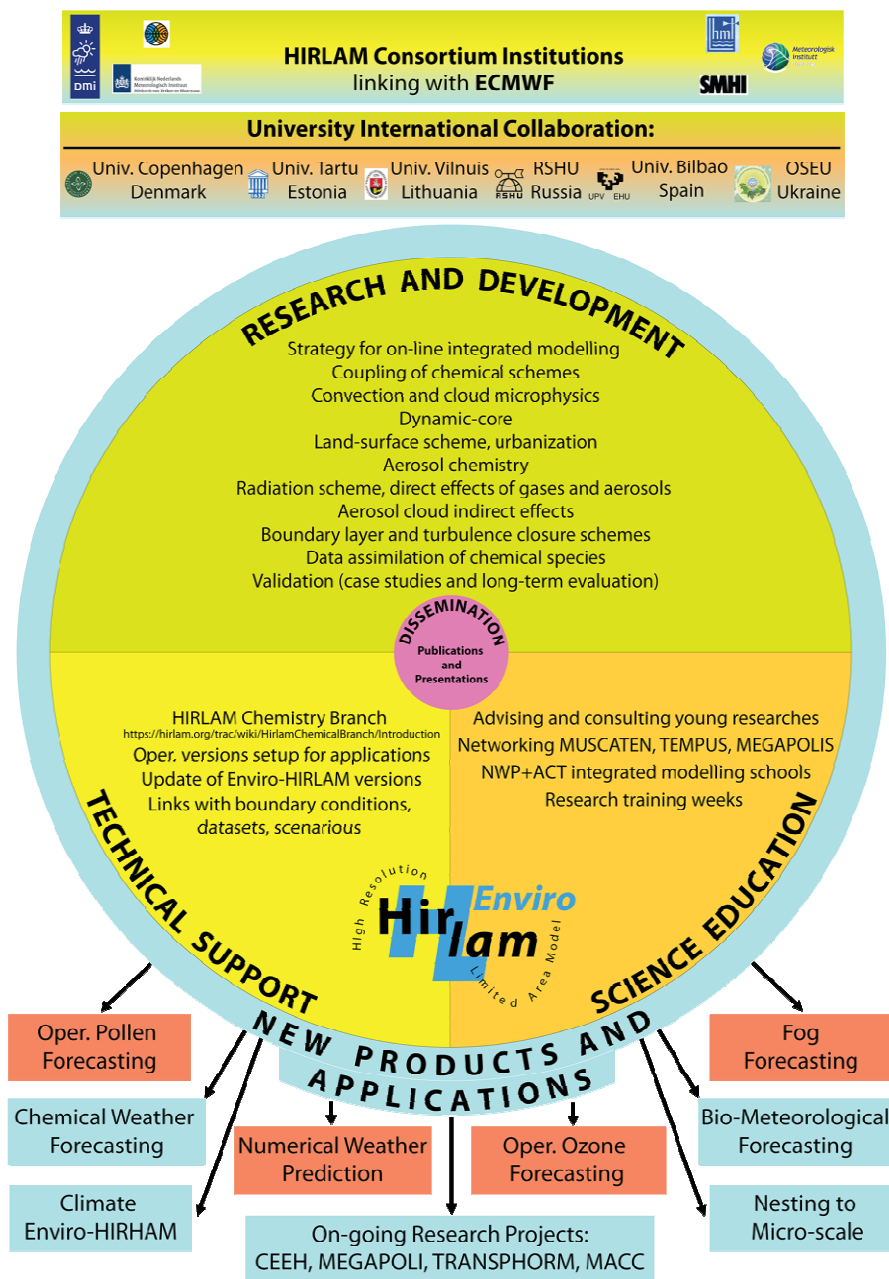
Figure 2.9 : Schematic description of activity in the frame of on-line coupled Enviro-HIRLAM (Environment – HIgh Resolution Limited Area Model)

Enviro-HIRLAM includes two-way feedbacks between air pollutants and meteorological processes. Atmospheric chemical transport equations are implemented inside the meteorological corner on each time step (*Chenevez et al., 2004*). To make the model suitable for CWF in urban areas, where most of the population is concentrated, the meteorological part is improved by implementation of urban sublayer modules and parameterisations (*Baklanov et al., 2008b*). The aerosol module in Enviro-HIRLAM comprises two parts: (i) a thermodynamic equilibrium model (NWP-Chem-Liquid) and (ii) the aerosol dynamics model CAC (*Gross and Baklanov, 2004*) based on the modal approach. Parameterisations of the aerosol feedback mechanisms in the Enviro-HIRLAM model are described in *Korsholm et al.* (*2008*) and *Korsholm* (*2009*). Several chemical mechanisms could be chosen depending on the specific tasks: well-known CB-IV, RADM2 and RACM or new-developed economical NWP-Chem (*Korsholm et al., 2008*). Validation and sensitivity tests of the on-line versus off-line integrated versions of Enviro-HIRLAM (*Korsholm et al., 2008*) showed that the online coupling improved the results. Different parts of Enviro-HIRLAM were evaluated versus the ETEX-1 experiment, Chernobyl accident and Paris study datasets and showed that the model performs satisfactorily (*Korsholm, 2009*).

DERMA

The Danish Emergency Response Model of the Atmosphere (DERMA) is an off-line three-dimensional Lagrangian long-range dispersion model using a puff diffusion parameterisation, particle-size dependent deposition parameterisations (*Sørensen, 1998*; *Baklanov and Sørensen, 2001*; *Sørensen et al., 2007*; *Baklanov et al., 2008*); and having two options of integration - forward and backward in time (Figure 2.10). Earlier comparisons of simulations with the DERMA model versus the ETEX experiment involving passive tracer measurements gave very good results (*Graziani et al., 1998*). The main objective of DERMA is the prediction and assessment of the atmospheric transport, diffusion, deposition and decay of a plume within a range from about 20 kilometres from the source up to the global scale.
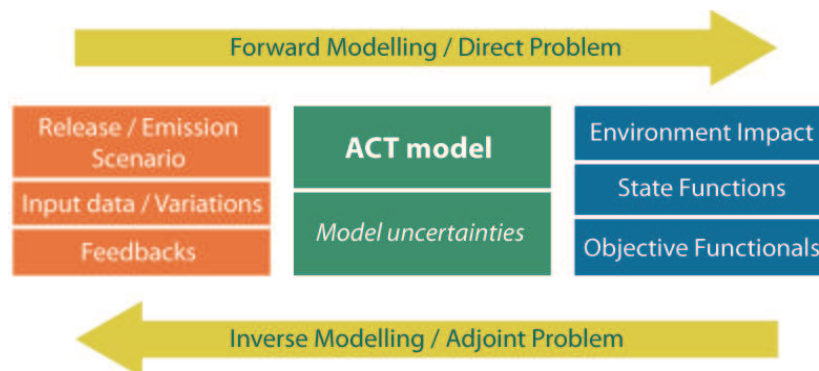
Figure 2.10 : Simplified scheme of the environmental risk assessment and mitigation strategy optimization basing on ACT model and forward/inverse modelling.

The inverse technique of the DERMA model is used in CEEH for risk/ impact minimization of damaging effects on the environment and public health from new planned national power plants and it helps to find zones for optimal construction of new plants. Methodological aspects of the sensitivity theory and inverse modelling for environmental risk assessment and emission control, e.g. estimation of source term, environmental risk/vulnerability areas, etc. are described by Baklanov (2007), Penenko and Baklanov (2001), Penenko et al. (2002, 2010).

Downscaled high-resolution models

The ACT models described in the above sections simulate the regional background air pollution (Figure 2.11). Urban and street air pollution is usually higher than pollution in rural areas and associated with significant adverse health effects. Prediction of health effects and implementation of urban air quality information and abatement systems require accurate simulation of air pollution episodes and population exposure, including modelling of atmospheric pollutions on city and street levels, as well as the indoor-outdoor relationship of the pollutants.
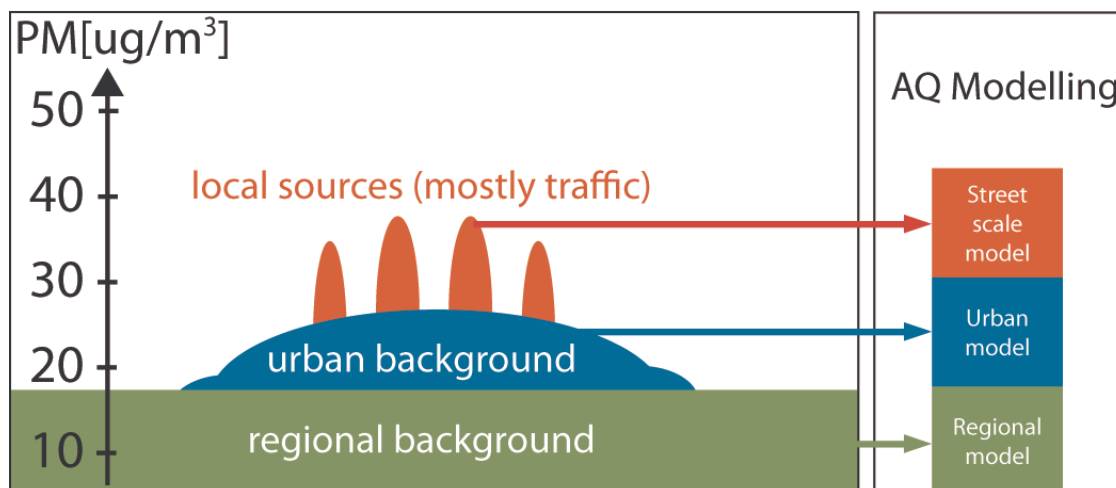
Figure 2.11: Specifics of scale-dependent AQ characteristics: regional background, urban background and street level concentrations and the multi-scale ACT modelling approach (Courtesy of N. Moussiopoulos).

Exposure is a mediating link between man and the environment; the health effects, actually having a causal association with air pollution, must be caused by personal exposures of the affected individuals (*Ott, 1995*). Personal exposures have been, however, found to correlate poorly with ambient air quality on the regional scale (*Koistinen et al., 2001; Kousa et al., 2002ab; Oglesby et al., 2000*). Personal exposures differ from ambient air quality, as characteristically a majority of time is spent in specific micro-environments: street canyons transport or indoor, where the building envelope filters some of the ambient pollution, and indoor pollution sources affect air quality. The presence of individuals in the

vicinity of the emission sources, especially in traffic, may also substantially increase exposure, compared with the data based on the regional scale ACT modelling.

As a result, air quality modelling needs in specific cases to consider a multi-scale modelling approach for urban areas with down-scaling by different models from meso- and city-scale with parameterisations of sub-grid urban effects to the local- and micro-scales with the obstacle-resolved approach. In CEEH several below described urban and street-scale models of different level of complexity are developed and used by DMU and DMI.

UBM

The Urban Background Model (UBM) calculates the urban background air pollution based on emission inventories with a spatial resolution down to 1 km x 1 km. Regional scale air pollution concentrations from DEHM are subsequently used as input to UBM. UBM is suitable for calculations of urban background concentrations when the dominating source is road traffic. For this source the emissions take place at ground level, and a good approximation is to treat the emissions as area sources, but with an initial vertical dispersion determined by the height of the buildings. The applied emission data have to be provided on a grid with the same resolution as used in the model. The concentrations calculated by UBM include NO, NO_2, NO_x, O_3, CO, benzene and particles. Contributions from the individual area sources, subdivided into a grid with a resolution down to 1 km x 1 km, are integrated along the wind direction path assuming linear dispersion with the distance to the receptor point. Horizontal dispersion is accounted for by averaging the calculated concentrations over a certain wind speed dependent, wind direction sector, centred on the average wind direction. Formation of NO_2 due to oxidation of NO by O_3 is calculated using a simple chemical model based on an assumption of photochemical equilibrium on the time scale of the pollution transport across the city area. This time scale governs the rate of entrainment of fresh rural O_3. The model is described in detail in *Berkowicz* (*1999b*) *and Brandt et al. (2001).*

OSPM

The output from UBM is used as input to OSPM (Operational Street Pollution Model). OSPM model predicts air pollution at street level at both sides of the streets in cities. OSPM is a parameterized semi-empirical model making use of a priori assumptions about the flow and dispersion conditions in a street canyon. In the model, concentrations of exhaust gases are calculated using a combination of a plume model for the direct contribution and a box model for the recirculation part of the pollutants in the street. The parameterization of flow and dispersion conditions in street canyons was deduced from extensive analysis of experimental data and model tests. Results from these tests have been used to improve the model performance, especially with regard to different street configurations and a variety of meteorological conditions. The model calculates air concentrations of NO, NO_2, NO_x, O_3, CO, benzene and particles in the street canyon at both sides of the street. Depending on the meteorological conditions, the air pollution concentration levels can be very different at the two sides of a street, due to the circulation of air in street canyons. OSPM has been successfully tested for many different cities in the world (*Berkowicz, 1999a, Brandt et al. 2001*).

M2UE

The M2UE (Micro-scale Model for Urban Environment; *Nuterman, 2008*) is an integrated Computational Fluid Dynamics (CFD) micro scale model for analysis of atmospheric processes and pollution prediction/assessment in the urban environment, which takes into account a complex character of aerodynamics in non-uniform urban relief with penetrable (vegetation) and impenetrable (buildings) obstacles and traffic induced turbulence (Figure 2.12). The model includes steady/ unsteady three-dimensional system of Reynolds equations, two-equation k-ε model of turbulence, the 'advection-diffusion' equation to simulate pollution transport, and a chemical solver. The numerical solution is based on implicit time advancing scheme and finite volume method. M2UE was evaluated by experimental data obtained from the TRAPOS project (Optimization of Modelling Methods for Traffic Pollution in Streets) and COST-732 Action which was devoted to Quality Assurance and Improvement of Microscale Models. In general, the model showed good and realistic results (*Nuterman et al., 2008; Baklanov & Nuterman, 2009*).

Source of pollution

       (a)   (b)
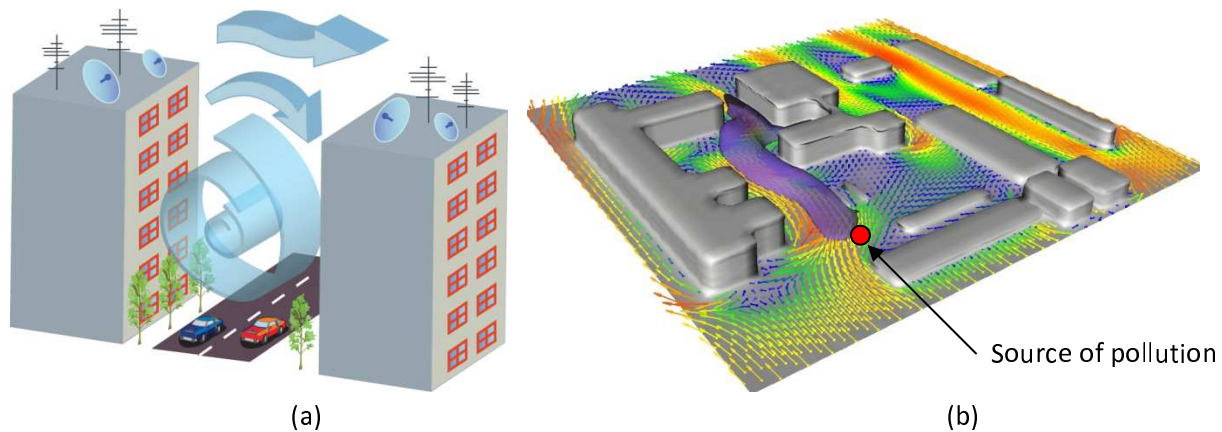
Figure 2.12 : (a) Schematic view of typical element of urban canopy – street canyon; (b) Wind flow and pollution dispersion for the part of Copenhagen area.

2.4. Meteorological models and climate data

Meteorological models (MetMs) are needed for providing input data to run and drive the atmospheric chemical transport models. The meteorological model calculates, with fine temporal and spatial resolution, three-dimensional fields of wind, temperature, relative humidity, pressure, turbulent diffusivity, clouds, and precipitation, which are used by ACTMs. Therefore the ACTMs, considered in the previous Sections, have to be directly coupled with MetMs or driven by output datasets from MetMs. In CEEH this is realised with several levels of complexity of the MetMs, and of the coupling to ACTMs:

1) Off-line coupling:

- separate ACTMs driven by meteorological input data from meteo-preprocessors, measurements or diagnostic models,

- separate ACTMs driven by analysed or forecasted meteodata from NWP archives or climate scenario datasets,

- separate ACTMs reading output-files from operational NWP models or specific MetMs at limited time intervals (e.g. 1, 3, 6 hours).

2) On-line coupling or integration:

- on-line access models, when meteodata are available at each time-step (possibly via a model interface as well),

- on-line integration of ACTM into MetM, where all possible feedbacks (e.g. aerosol forcing on radiation and cloud processes) may be considered. This definition is used for on-line coupled/integrated modelling.

Most of the ACTMs used in the CEEH modelling framework are realising the fist way of (*off-line)* coupling. Only the Enviro-HIRLAM and M2UE models are *on-line integrated* models.

For planning and optimization of the energy system, as well as for the health effects assessments and estimation of externality cost functions usually long-term simulations (at least for one full year) are needed. Therefore we have chosen the year 2000 as the reference year for long-term simulations in our current CEEH studies. In principle any other periods (previous and current years or future climate scenarios) could be used for modelling studies. However, it is noted that the so-called North Atlantic Oscillation (NAO) index varies quite strongly from winter to winter, telling that this is also the case for westerlies and south-westerlies in winter over northern Europe. Since the general wind direction and speed is important for the transport of chemical species one should not choose a year with exceptionally high or low NAO index. The index in year 2000 was relatively high (see Figure 2.13) but since we are using the weather in year 2000 for all our simulations the relative bias due to NAO is the same for all model simulations.
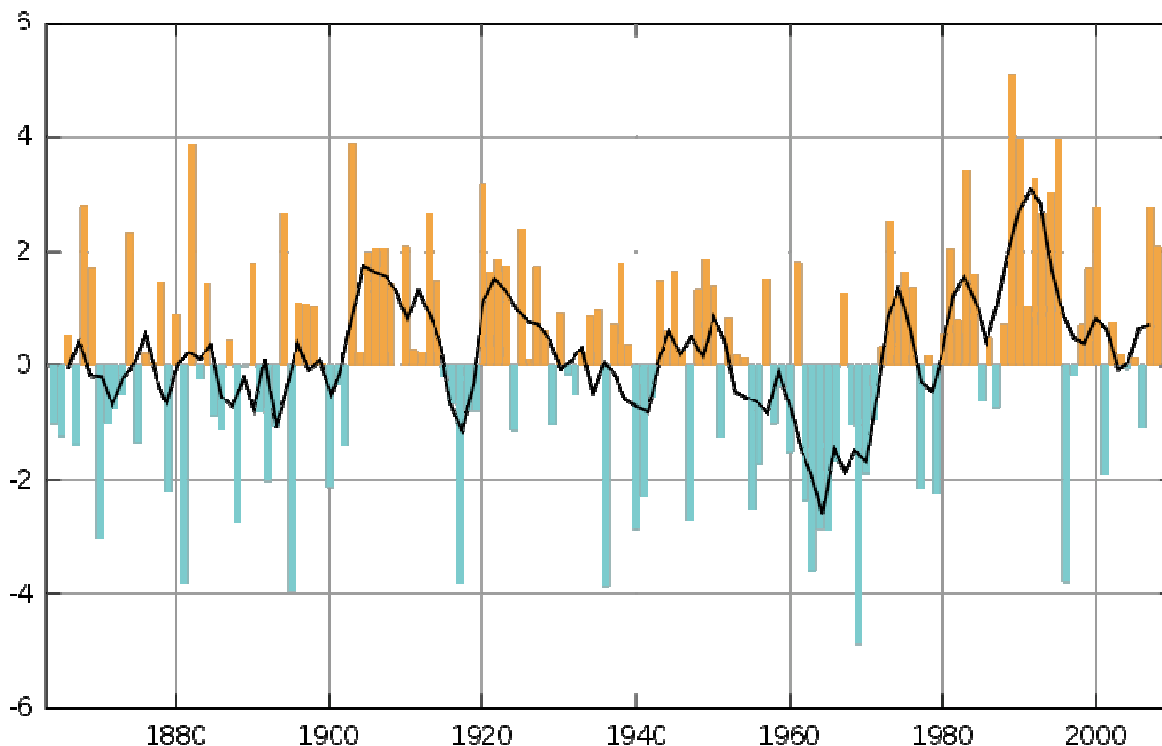
Figure 2.13. The NAO index for the period 1870–2009 AD. It is defined as the anomalous difference between the Icelandic low and the subtropical high (Azores) during the winter season (December through March).

In the CEEH modeling chain the different meteorological models and datasets, depend on the scale considered, the selected domain of interest and the type of ACTM can be used. For the global or regional scale simulations we use meteorological data from the European Center for Medium-Range Weather Forecasts (ECMWF) archives (ERA-40, etc.), based on the ECMWF IFS global model forecast and analysis system, or the US National Centre for Environmental Prediction (NCEP). ECMWF or NCEP global re-analyzed meteorological data are used to define initial and boundary conditions for the limited area NWP models. Data from the global circulation models are the starting point for regional weather forecasts by national weather services (by DMI for Denmark).

For Denmark and Europe the DMI-HIRLAM operational weather forecast model (*Sass et al., 2002*) and archived meteo-datasets are used by CAC/CAMx, DERMA, and for boundary conditions by Enviro-HIRLAM.

The hemispheric/regional-scale DEHM and urban background UBM models use meteorological data from either the MM5v3 (*Grell et al., 1995*) or the Eta model (*Janjić, 1994*).

HIgh Resolution Limited Area Model (HIRLAM)

The High Resolution Limit Area (HIRLAM) numerical weather prediction model (*Unden et al., 2002; Sass et al., 2002*) has been run operationally by DMI (http://www.dmi.dk) for the European territory and for the Arctic region since the late 1980s. But it can be run also, after extending the grid domain, for other geographical regions. The operational system consists of three nested models. At present, output from several nested versions of DMI-HIRLAM is applied (Figure 2.14):

- T15 – horizontal resolution 15x15 km, 40 vertical layers;
- M09 – horizontal resolution 9x9 km, 40 vertical layers;
- S05 – horizontal resolution 5x5 km, 40 vertical layers;
- S03 – horizontal resolution 3x3 km, 40 vertical layers;
- U01/I01 – horizontal resolution 1.4x1.4 km, 40 vertical layers (experimental urban version).
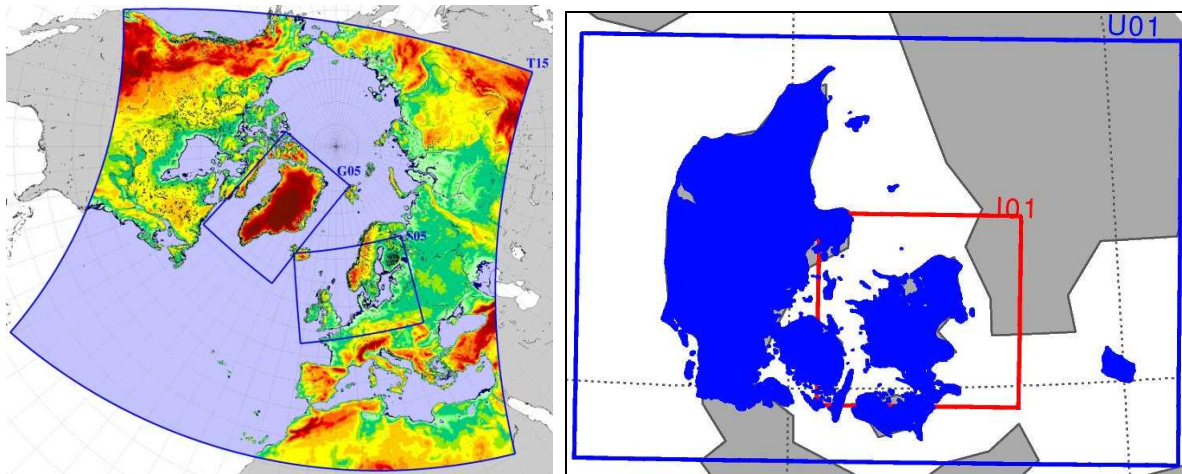
Figure 2.14: Examples of operational and research NWP DMI-HIRLAM modelling areas.

An interface between the NWP and ACT models was built. Through this interface necessary information is extracted from the HIRLAM output, and then it is used by the ACT model.

The DMI-HIRLAM dataset for CEEH simulations for the year 2000 was prepared by optimised runs of the HIRLAM T15 version with the horizontal resolution of 15 km for the major part of the Northern Hemisphere (see Fig. 2.14). This dataset is used by both the DMI ACTMs: as a meteorological driver for the off-line coupled system, and as boundary and initial conditions for the on-line coupled Enviro-HIRLAM. For the Northern Europe and Denmark the horizontal resolution can be increased up to 5, 3 or 1.4 km.

ECMWF Dataset

The meteorological data from the European Centre for Medium-Range Weather Forecasts (ECMWF), Reading, UK are based on the ECMWF's ISF global model forecasts and analyses (http://www.ecmwf.int) having a resolution up to 0.5° × 0.5° latitude vs. longitude and 3 hours time interval for both Northern and Southern hemispheres. Analysis has been done on a daily basis at 00, 06, 12 and 18 UTC terms.

The ECMWF has the following data archives: ECMWF/WCRP level III-A Global Atmospheric Data Archive (TOGA), Operational Atmospheric Model, ERA-15 (ECMWF Re-Analysis 15), ERA- 40 (ECMWF Re-Analysis 40), Wave Model, Ensemble Prediction System (EPS), Seasonal Forecast, and Monthly Means.

The ERA-15 production system generated re-analyses from December 1978 to February 1994. The ERA-15 Archive contains global analyses and short range forecasts of all relevant weather parameters, beginning with 1979, the year of the First GARP Global Experiment (FGGE). The Level III-B archive is subdivided into three classes of data sets: Basic 2.5° x 2.5° Data Sets (17 vertical pressure levels); Full Resolution Data Sets (e.g. 1° x 1°, 31 hybrid model vertical levels); Wave archive.

The reanalysis project ERA-40 (*Simmons and Gibson, 2000*) covers the period from mid-1957 to 2001 overlapping the earlier ECMWF reanalysis, ERA-15, 1979-1993.

In this particular study we used ECMWF data, available at DMI for the forecast mode or analysed and archived mode. The horizontal resolutions of the meteorological data are different from year to year. For example, for the year 2000 the data have a resolution of 1° x 1° latitude vs. longitude and 6 hours time resolution. It consists of temperature, u and v components of horizontal wind, and specific humidity at each level, plus surface fields. Analyses have been done at 00 and 12 UTC.

Climate model scenario datasets from DMI DCC

The influence of estimated anthropogenic climate change on transport and chemical processes at different years (see WP6) is also considered in CEEH. The Danish Climate Centre (DCC) at DMI is providing meteo/climate datasets of different climate change scenarios. This is then used as meteo/climate input data instead of the standard year 2000 meteorological data mentioned above. In this way the sensitivity of air pollution to changing background climate is investigated. For example, several climate change scenarios, simulated at DMI DCC by the ECHAM5-OM model, have been used as meteorological driver to study the climatic change impact on air pollution levels (*Hedegaard et al., 2008*).

2.5. Population exposure and health impact assessment

Population exposure and health impact assessment models use air pollution concentration data from ACTMs as input and simulate health effects based on a health effect model. Health costs are then estimated using a set up of health cost functions.

CEEH is operating with two different model lines for evaluating health impacts and social costs. One line uses the integrated model system EVA (Economic Valuation of Air Pollution) that simulates/includes emissions, atmospheric dispersion and chemistry, human exposure, human health damage and social costs based on the impact pathway methodology. The other line, the CEEH Health Impact Assessment (HIA) line, is build up of a separate ACT part and a HIA part. Basically both lines consist of an emission module, an ACT module, a health effect model that quantifies health damage, and a set up of cost functions for evaluation of social costs of health damage. The emissions module is the same for the EVA and HIA lines.

2.5.1 The EVA health effect model

EVA (Economic Valuation of Air Pollution) is a newly developed integrated model system. The system includes modules for air pollution, human health and economic impact. The system has been developed for the valuation of site-specific health costs related to air pollution (*Andersen et al., 2007*). The EVA model system is based on the impact-pathway approach developed by ExternE (*Friedrich and Bickel, 2001*). The air pollution in the EVA system can be calculated from the regional (DEHM) and local (UBM) dispersion models. DEHM and UBM have been described in chapter 2.3. The EVA system is described in detail in CEEH report No. 3 *(Brandt et al., 2011).*

A module in EVA couples the results from the air pollution model(s) with address-level population data for Denmark in the year 2000 with concentration-response functions derived from literature and costs functions developed specifically for Danish conditions in order to obtain estimates of a particular source impacts and costs. For details concerning the exposure-response and cost functions, see *Andersen et al., (2007)*.

In Figure 2.15 it is shown how exposure is estimated. The top/left map shows annual average air pollution concentration data on a geographical grid. The next map shows the population density distribution in different geographical areas, and the bottom/right map shows the population exposure.
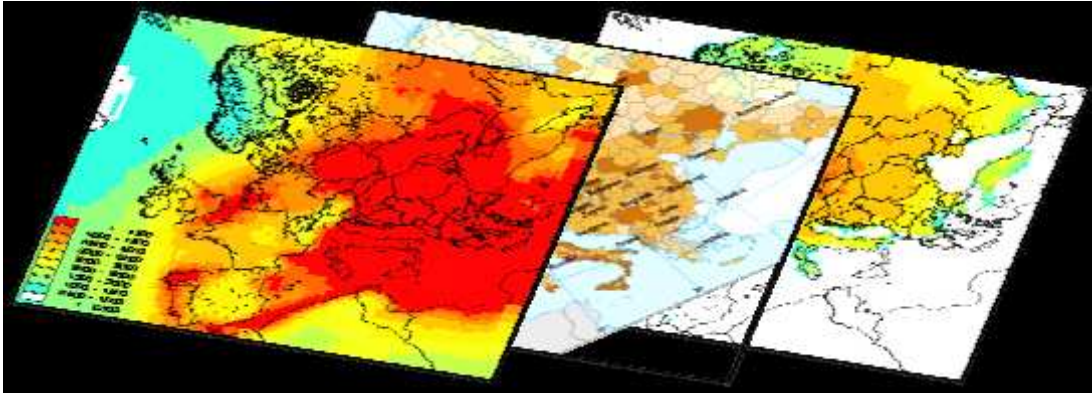
Figure 2.15 Air concentration times Population Density = Exposure

The health effect model used in EVA is based on best estimates from WHO and EU used also in the Clean Air for Europe (CAFÉ) calculations (*Watkiss et al., 2005*). Pollutants included in EVA are the following: SO_2, O_3, $PM_{2.5}$ (primary), nitrate, sulphate, and CO.

2.5.2 Development of a new health impact assessment model in CEEH

A new health impact assessment (HIA) model is being developed (see next section), but it may be implemented in the EVA system at a later stage.

Two WPs of CEEH (WP3 and 4) are focusing on the health impact studies. The purposes of WP3 are 1) to quantify the relative risks of different pollutants on respiratory and cardiovascular diseases on the basis of literature studies, 2) to investigate the effect of the chemical composition on toxicological impact, 3) to build health risk input for a health impact assessment model in WP4. The purposes of WP4 are 1) to quantify the health impact of pollutants on a macro-scale level based on statistical methods and inputs from WP2 and WP3, and 2) to set up health cost functions for the different emission scenarios from WP1 in a way suitable for the energy-system optimisation models.

The HIA model, developed in CEEH, is based on the epidemiologic literature from which risk estimates for respiratory and cardiovascular diseases as well as other diseases are identified. Both morbidity and mortality risks will be estimated and specified for specific diagnoses. High emphasis will be put on concentration-response estimates in the cases where these have been estimated and non-linear responses may have to be accounted for in some cases. Currently, the known studies suggest that for most of the relevant pollutants there is no identifiable lower limit of effect. When possible and relevant, separate estimates will be assigned to different age groups and gender as well as those with pre-existing co-morbidities. The risk estimates are established as relative risks from the literature. In order for these to be applied in the models, the size of the population at risk and the average risks of the population need to be taken into account. These statistical data are obtainable from existing registers.

Selection of air pollutant species in CEEH

The pollutants in the CEEH models have been selected based on the following criteria:

- They stem from combustion sources either directly or via chemical transformations. This may include evaporation or dust from the energy sources themselves (i.e. from wear and tear). Other pollutants derived from energy production but not liberated to the air is not included (e.g. heavy metals in soil deposits). However, heavy metals, dioxins and possibly PAHs that are emitted to the air, deposit on soil or in water and end up by being ingested should ideally be covered by CEEH.

- They can be modeled in the CEEH settings.

- They are sufficiently investigated in terms of documented health effects.

Combustion sources and accordingly combustion products are highly diverse and widespread. In practice, therefore, not all sources that contribute to health effects in humans can be included in the CEEH models.

Pollutants in existing models: Different models exist and include varying combustion products. This review does not claim to include all existing models used previously but emphasizes a few models considered particularly relevant for the CEEH modelling of health effects from combustion products in Denmark. A review of coronary heart disease models has been published (Unal et al., 2006) and a Dutch PhD study on methods and validity of HIA models was finished in 2007 (Veerman, 2007). User friendly HIA models are in great demand and still no such models are available for valid quantifications of air pollution impacts on health (Brønnum-Hansen, 2009).

Other pollutants proposed in the literature: Other pollutants than those in EVA contribute to the adverse health effects of (combustion-derived) air pollution. It is the dominating opinion, that these include ultrafine particles with a diameter greater than 2.5 μm (PM_{10} or PM_{10}-$PM_{2.5}$), black smoke, ultrafine particles, and CO. Numerous scientific studies either document or are highly suggestive of separate effects of these components. The composition of particles is important too and there is evidence of effects not related to the dominating sources of particles in EVA (nitrate and sulphate). Substances that appear to be important in this respect are metals, PAHs, and biologic material that aggregate with the particles and are carried into the lower airways by them, such as endotoxins. Several publications suggest effects of NO_2 or other NO_x. The dominating opinion is, however, that the contribution from NO_x is either via contribution to O_3 - a pollutant with effects separate from those of particles or in case of possible separate effects of NO_x these are indistinguishable from those of fine particles due to the high correlation with other combustion derived pollutants such as particles. Recently, aldehydes from bioethanol have been shown to add importantly to the toxicity from of this type of fuel. The effects of aldehydes appear to be mediated almost entirely through O_3-generation.

Some of these additional pollutants have short life-spans in the atmosphere or are rapidly diluted and do only have health effects within short distances of the source. This appears to be the case for ultrafine particles and CO. The relevance of modelling these is therefore limited except in models of health effects of pollution from traffic.

In addition to combustion products another type of pollution is traffic noise, which adds to the observed morbidity and mortality, but which has been studied to little for meaningful assessment in the CEEH chain.

Recommendations for CEEH: As there is consensus that the most important health effects (also in terms of costs) stem from particles, CEEH should include effects of particles composed of nitrates and sulphates as well as primary particles in the size fractions PM_{10} and $PM_{2.5}$. Effects of particulate matter include all-cause or cause-specific morbidity (as hospital admissions) and mortality for both adults and infants. Ozone should be modelled in CEEH to use of a RR for long-term effects on all respiratory mortality. The gaseous pollutants SO_2, O_3, and NO_x should also be modelled. In contrast to other recent reviews, but from the point of view that independent effects of SO_2 do seem to exist and that they are plausible from a mechanistic point of view and despite the risk of double counting effects in CEEH we propose a short-term CRF of SO2.

Separate effects of NO_x, VOC, and CO are presently not well-enough documented and too small for reasonable inclusion in the overall models. However NO_x emissions contribute to secondary particles and to ozone and are important in the atmospheric modelling and generate important health effects through PM and ozone. New studies regularly appear in which NO_x has been used as the primary (only) pollutant adding new information about health effects of air pollution. In CEEH we therefore do attribute an effect of NO_2 on incidence of COPD (Chronic obstructive pulmonary disease). CO is a well-known highly toxic gas released from combustion in particular when oxygen supply is insufficient, i.e. under poor combustion conditions. In models of traffic, CO and ultrafine particles will be relevant to add. NOx and VOC may be relevant too, especially in models evaluating bio-fuels. Ideally noise should also be included in models of traffic-generated air-pollution.

PAH not restricted to dioxin should be modelled as should the metals As, Cd, Cr, Hg, Ni and Pb. Metals such as Fe, present in combustion-derived particles and potentially responsible for specific toxicity, remain to poorly documented for specific modelling of health effects. Although heavy metals originate to a large extent from combustion sources, and health effects of lead and mercury are well documented, heavy metals are not considered in CEEH. However, their effect may be contributing to the general toxicity of fine particles. Further their major effect come from uptake via food and water, which is not considered in CEEH.

Table 2.1 : Air pollutants in CEEH and their effect on health. The grey fields show the most important primary pollutants in CEEH.

Pollutants	Impacts
Particulate matter (PM_{10}, $PM_{2.5}$) (Primary, SO_4^{2-}, NO_3^-)	Include all-cause or cause-specific morbidity (as hospital admissions) and mortality for both adults and infants
O_3	long-term effects on all respiratory mortality
SO_2	Short-term effects
NO_2	COPD (Chronic obstructive pulmonary disease).
NO_x	Health effects through $PM_{2.5}$ and O_3
NH_3	Health effects through $PM_{2.5}$
NO_x+VOC	Effects not well enough documented and too small. Relevant in modeling health effects of biofuels.
CO and ultrafine particles	Effects not well enough documented and too small. Relevant in modeling health effects of traffic.
PAH diesel soot, benzene, 1,3-butadiene, dioxins	Cancers – effects may be modeled but not validated
As, Cd, Cr-VI, Ni	Cancers, other morbidity– effects may be modeled but not validated
Hg, Pb	morbidity (neurotoxic) – effects may be modeled but not validated

2.5.3 CEEH Health Impact Assessment (HIA) model

The EVA versus the CEEH HIA methodologies

There are several reasons for applying and developing the two different model lines, EVA and HIA, in CEEH:

- The HIA-line is designed in such a way that the effects of the expected demographic development up to 2050 can be directly incorporated into the system. This is important since the aging of the population will most likely impact concentration response functions because the impact of air pollution levels on human health depends on the population distribution and density, type of activities, protection measures, risk perception, etc. (*FUMAPEX, 2005*). Obviously, externality costs will therefore also be modified significantly.

- The EVA line is based on the simple impact pathway methodology, which for many years has been the standard method for supporting policy making and decision support as e.g. in the CAFE reports (Watkiss et al., 2005).

In the HIA-line effects on the Danish population will be calculated based on demographic data for different risk categories. As air pollution exposure data are not available at the individual level indirect methods and macro simulation models are needed to quantify the health impact of air pollution as those developed in relation to studies of the impact of tobacco smoking and other risk factors (*Peto et al., 1992*; *Baan et al., 1999*; *Brønnum-Hansen, 1999*). The applied methods will be based on input from the dose scenario outputs in WP2 and the physiological investigations in WP3.

The construction of health cost functions will require a truly multidisciplinary effort where the feedbacks in the energy-system optimisation models must be understood. An important component will be to analyse and understand the uncertainties in final cost functions, used as a basic input in WP5.
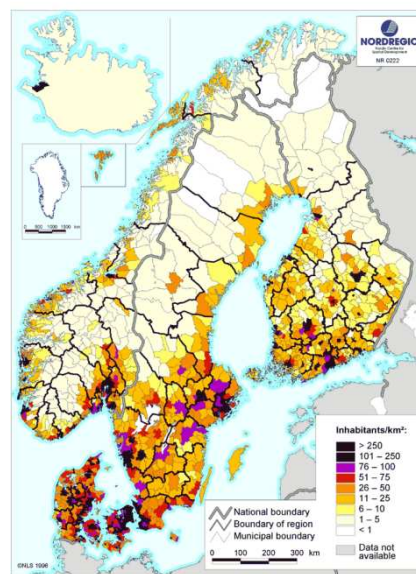
Figure 2.16: Population density in the Nordic countries

Structure of the CEEH Health Impact Assessment (HIA) model

The *Health Impact Assessment* (HIA) model includes demographic and epidemiological modeling for assessment of the impact of changes in the exposure to risk factors for selected indicators for health and mortality in the Danish population and the resulting health service costs and cost to society of production loss (Figure 2.17). In particular the model includes assessment of the impact of air pollution in scenarios for future Danish energy production.

Input

WP2 and WP5 input: Exposure composition and air pollution distribution for different energy/emission scenarios	**Demographic input:** Population data, age distribution, geographical distribution, fertility and mortality rates, population forecasts
WP3 input: Parameters of concentration-response (morbidity/mortality) associations (relative risks)	**Health Impact Assessment Model**
Costs input: Health care resource units, Diagnosis Related Groups (DRG). Labour costs	**Morbidity input:** Baseline hospitalizations and cause of death (respiratory and cardiovascular diseases)

Output

Population health indicators:
- Future mortality (all causes and cause specific)
- Hospitalizations (respiratory and cardiovascular diseases)
- (Quality-Adjusted) Life expectancy
- Disabilities

Health care and social costs:
- Health sector costs (primary and hospital care)
- Social sector costs
- Absence from the work force
- Societal production

Output for WP5 and WP6: Additional cost functions due to health impact for energy system optimisation

Figure 2.17: Scheme of the CEEH Health Impact Assessment model (HIA model).

The project's *Health Impact Assessment* model will comprise the following elements:

- A demographic module, including a population forecast.

- An epidemiological module quantifying the consequences for health (morbidity and mortality) by use of parameters of association between exposure and health.

- An economic module which values the consequences as to health care costs and social costs.

Demographic Module

The aim is to include the demographic forecast in the Danish population during the years 2000 to 2050 in the model. The inclusion of a realistic demographic scenario for Denmark will be based on already established projections (e.g. population prognoses from Statistics Denmark). On the basis of those, the model should then be able to handle deviations from established projections in two areas. Firstly, the model should be able to operate on various breakdowns of the Danish population, for instance the present 98 municipalities or the 96 grid cells used by the atmospheric emission models in CEEH, and be able to take into account gender and age specific population figures for single units in accordance with established projections. Secondly, the model should be able to handle changes in mortality and perhaps fertility and the resulting prerequisite conditions for population projections.

Epidemiological Module

The aim is, on the basis of the demographic module, external health determinants and parameters of associations between risk factor exposures and morbidity and cause-specific death, to model the impacts of changes on morbidity and mortality, measured as prevalence of disease, number of hospital admissions, number of deaths, life expectancy and quality-adjusted life-years (QALYs). In addition, these changes in mortality and – if feasible – fertility should be integrated in the demographic modeling.

In relation to CEEH, the focus of the model should be on the outcomes from cardiovascular and respiratory diseases with input from the Danish National Patient Register and the Cause of Death Register, both about specific disease and mortality outcomes and estimates of relative risks.

Economic Module

The aim is, on the basis of the health outcomes from the impact modeling, to quantify the resource use and cost of modeled changes in morbidity and mortality. This will be done in a framework of attributable cost, where the costs associated with a pollution related diseases are calculated as the difference in average cost for persons with and without the specific disease. The cost will focus on resources used to treatment and care in the primary and secondary health care service, and consequences for social production. Potential cost and savings from avoided premature deaths will also be estimated, as will the health care cost during the last life-year. The module will provide unit costs to the CEEH model, and the model chain will be applied to cost-effectiveness analyses of scenarios for future Danish energy production and the resulting air pollution.

Basic Structure of the Health Assessment Model

The modeling is based on the Danish population in the year 2000 disaggregated by gender and 1-year age groups as well as concentration-response estimates for the selected exposure and related morbidity and cause-specific mortality and the resulting health service costs.

An integrated and dynamic model will be designed including the demographic developments and quantifying changes in morbidity and mortality. The model will be constructed as a *Multi-state Markov Model* with states corresponding to both the age and gender distribution of the population and the included diseases, cause-specific deaths and mortality from other causes. The estimation of transition probabilities between states will be made on the basis of the unique possibilities of register linkage in Denmark. When life course data from Danish registers and cohorts are used, the actual estimation of transition probabilities can be made so that these fit in with conditions in Denmark and, thus, strengthen the model in two areas. Firstly, this strengthens the precision and validity of studies of treatments and interventions in Denmark and, secondly, the estimation allows direct estimating of uncertainties in the transition probabilities, and afterwards inclusion of these uncertainties directly in the model as opposed to a traditional sensitivity analysis. The impact of changed exposure is estimated through outcome measures obtained from the literature. Here the project should concentrate on the development of a standard procedure, which can estimate transition probabilities on the basis of the databases mentioned.

A *Multi-state Markov Model* can handle co-morbidity by expanding it by a number of extra states, just as competing disease outcomes and causes of death can be treated within the model by adjusting the transition probabilities. Thus, a *Multi-state Markov Model* is a very flexible framework, and the limit for detailing of the model is primarily determined by two factors: which and especially how detailed data are available as to morbidity, co-morbidity and competing causes of death, and the amount of computer capacity available.

Figure 2.18 shows the population prognosis for Denmark during the period for which CEEH makes projections. Marked changes in the population composition are seen, with more elderly and fewer young people. This is expected to affect the population's response to exposure to air pollution. The described *Health Impact Assessment* model takes these changes into consideration in the scenarios of the health consequences of air pollution.

(a)   (b)
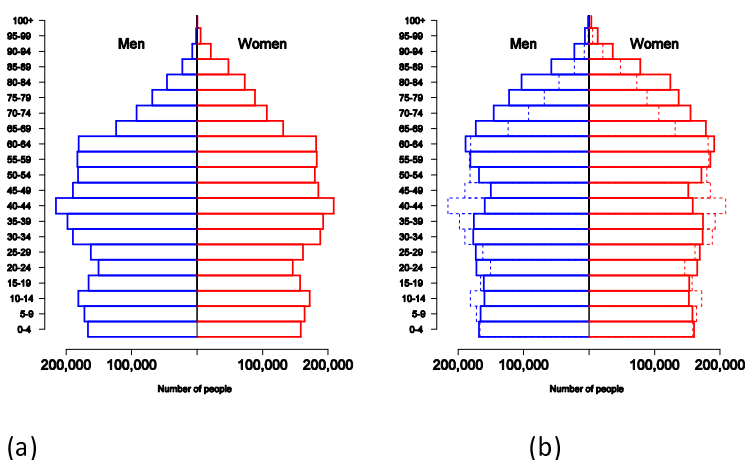
Figure 2.18 : (a) the Danish population in 2007, disaggregated by gender and 5-year age groups; (b) the projected Danish population in 2040, the broken line marking the population in 2007 (see Figure 2.11a) disaggregated by gender and 5-year age groups; Source: Statistics Denmark.

2.5.4 Social cost of diseases

The objective of this sub-component is to establish unit costs for application in the CEEH models. The unit cost relates to:

- Cost of health service related to diseases associated with air pollution
- Loss of work time and social production
- Loss of health related quality of life
- Savings in social consumption

- Valuations of avoided loss of life and avoided life year lost

The health service costs relate to individuals who become ill with diseases associated with air pollution (as identified in WP3). These unit costs will be applied to the estimations of the number of individuals who become ill due to air pollution from the demographic and epidemiological submodels in order to make value assessments of the consequences of changes in air pollution.

The unit cost associated with selected diseases will be defined as the mean cost that can be attributed to the specific diseases. An attributable cost is defined as the average additional cost for individuals with specific diseases in comparison to individuals without the disease. The attributable cost can in this context be interpreted as the incremental cost of the disease and may therefore also reflect the average additional cost for a person who experiences the disease.

The analysis will specifically focus on the cost in the last year before death as these health care costs are often considerable higher in comparison with previous years. In addition to the health sector cost, the analysis will also focus on the absence from work and provide an estimate for the loss of societal production.

Methods

Identification of individuals with disease

The basis for this analysis is data from the National Patient Registry from 2002-2008. This data source includes information about individuals' use of hospital and primary health services.

The relevant diseases will be defined according to the International Classification of Diseases (ICD-10) codes (WHO, http://www.who.int/classifications/icd/en/).

The database include a file with hospital admissions identified through a hospital record id and a file with diagnostic codes containing hospital admission record id, ICD-10 code and type of diagnostic code. Each hospital record might be related to several diagnostic codes. Each year has its own set of files.

An individual with the relevant diseases will be defined as a person who in the observation period has had at least one hospital contact (inpatient or outpatient) which was coded with the disease as a diagnosis (independent of type of diagnose – i.e. including action diagnosis, additional diagnoses, referral diagnoses and ground morbus).

Such identification of diseased individuals makes the assumption that if a hospital doctor once in the observation period has registered that the patient have the disease, then the patient is considered to be an individual with the disease.

Different methods of identifying diseased individuals will be tested, for example, by attempting to exclude individuals with "borderline" diseases (individuals with limited hospital care of the disease), e.g. by requiring that individuals should have two or more hospital contacts with the specified diagnosis.

Other definitions could rely on only action diagnosis (aktionsdiagnose), or combinations of additional diagnosis (bidiagnose), referral diagnosis (henvisningsdiagnose) or (grund morbus).

From the sample of individuals with the relevant diseases, only those, who were alive January 1, 2002 will be included in the cost analysis.

In the sample of patients there will be individuals who die during the observation period and the cost in the last year of their life will be estimated.

Health care costs

Cost data will be available for only a few years (2000-2008) due to changes in the systems of assigning cost to health services (the DRG-system). The cost data will include national DRG-cost data for all hospital contacts, fees paid for services rendered by the primary health care service and for all prescription medicine provided by the pharmacies in the primary care sector.

The resource use in the hospital service is defined in terms of numbers of hospital contacts. A contact can take place as a visit at the accident and emergency department, an outpatient clinic or as an inpatient admission. For each contact there is a description of the resource use associated with the contact based on the national diagnostic related group-system (DRG).

Resource use in the primary care sector is defined in terms of services provided by primary care providers who receive a fee from the public health insurance system. This sector includes general practitioners, privately practicing specialists, dentists, physiotherapists, chiropractors and others. Each service provided was associated with a fee paid to the provider. This fee can be interpreted to indicate the value of the resources use for the services. However, the fee structure is negotiated between the provider and purchaser organisations and does not necessarily reflect the true cost of the service.

Use of prescribed pharmaceuticals will be derived from registrations provided by primary care pharmacists. Medication provided by the hospital may be included in the hospital care cost, and were not included in the primary care pharmaceuticals. The pharmaceutical cost entails the full cost of the sale including parts of the sales price that may be paid by the health insurance system or the patients.

As the 2007/8 costs data can relate to the different time intervals after the diagnosis, some adjustment was necessary to take account of the difference in the time that the complication arose and the time for which cost data were available. This could be done since precise data for the time of the health service provision was available (date of hospital contacts, week for primary health care and date for the pharmacy's sale of drugs).

The analysis of resource use and costs may be devised in monthly/quarterly time intervals as described below.

The 2007/8 cost data will be related to months after the date of the first diagnose. The monthly resource use (cost) during the cost observation period will be related to the months (M) after the

diagnosis. A person who was diagnosed 1. January 2007 will thus have cost data for M1-M24, while a person who was diagnosed 1. January 2006 will have cost data for M24-M36.

The estimations will be based on the whole sample but the annual costs will be derived only for those individuals who have data in the particular years. The calculations will be aggregated from monthly data so the same individual can contribute data in two years. Therefore, the number of individuals who will have provided data for each year cannot easily be provided.

The cost estimates will be made as the annual cost for hospital care, primary care and prescription medication provided by the primary care pharmacies. It would be possible – in a subsequent analysis – to disaggregate the cost calculation into these components, as well as disaggregating the hospital care into cost relating to inpatient, outpatient and accident and emergency.

Analysis of days absent from work

Information about all sickness and leave cases registered by the Danish municipalities will be available for the analysis. For each individual there will be information about the type of sickness case and how it was ended. In addition there will be information about the amount paid to the employer and employee as subsidies, the number of days that subsidies were paid and the full number of sickness days (i.e. including the first 14 days of the sickness period where no subsidies were paid). The same person can have several sickness cases during the year. This might indicate that the person has several periods of illness during the year or it may be that the person has more than one employer (two part time jobs) and that there have been paid subsidies to both. The data set did not include any dates. In the preparation of the data set the number of days absent from work has been aggregated for each individual. If there were two records for the same person with identical number of sickness days it has been assumed that the person has had two employers and that the subsidies have been paid to both. In these cases the amount paid as subsidies has thus been accumulated but not the days of sickness.

Only absence relating to personal illness has been included (sagsart code 11, 12, 13, 14, 17 and 22). Subsidies and absence relating to child births and sabbatical leave were therefore excluded from the data set.

Data on socioeconomic status were also available. This variable includes the most frequent status during the year. The codes include retirement due to old age (code 322), early retirement (code 321) and voluntary retirement (code 323). Other codes indicate in employment, unemployed, under education and children.

All observations of days absent from work will be truncated at 365 days.

It is desirable to obtain estimates of days absent from work for individuals with specific diseases during the first year of complication and during subsequent years. In the first case the estimated mean sickness days will be estimated for individuals with the diseases and compared with all other individuals in the sample.

The analysis might be repeated for people registered with early retirement, old age pension and early voluntary retirement excluded.

Assuming normal distribution of the sickness duration the simple t-test was employed to test differences between the two groups. A significance level of 5% was employed.

Health Related Quality of life associated with disease

Loss of health related quality of life will be established for individuals with the relevant diseases in age and sex related groups. This assessment will apply to data where generic HRQoL instruments have been applied and estimates found in the literature. Preference will be given to data that include assessment using the generic EQ-5D instrument or various versions of the SF-36 instruments. Datasets that apply to other generic instruments will be considered and included if found relevant.

The HRQoL-scores will be applied as weights indicating the loss of quality of life of individuals with the various diseases.

Consumption of other resources

When individuals die they will not make use of social resources (e.g. public services, housing, food, travel and leisure activities). An assessment will be made to establish age and gender related cost of consumption of other resources. Such social savings will be applied for each individual who experiences premature deaths, and would thus off-set the resource in the health care sector.

Cost associated with death and life years lost, and environmental damage

The social values of life and life-years lost will be established through review of the scientific literature. There are considerable methodological and practical challenges in establishing such values and especially in the relationship between the value of life and the value of life years lost. The review will examine and assess the choices made in previous studies. Based on published studies, an attempt will be made to derive a set of realistic values for the CEEH model.

Amalgamating the costs

The cost assessments described will provide unit costs to the CEEH model. The unit costs may be assumed to represent societal cost under special circumstances (e.g. assuming constant return to scale in production, constant valuation etc.).

However, such assumption might not be valid when modelling large changes in resource use. Therefore, some adjustments to the unit cost will be proposed to adjust the unit cost to more realistic levels.

Chapter 3. Model parameters specification and data exchange in CEEH modeling framework

3.1. Data flow and input/output between the models in the CEEH framework

The individual models and modules in the CEEH modelling framework need not necessarily be integrated into one modelling system. They can be run independently on different computers and by different organisations and teams. However, they have to be linked via data flow, therefore the input/output (IO) file formats between the ones within the CEEH framework have been specified and harmonized to successfully perform iterations within the framework.

The scheme below (Figure 3.1) was built to display data exchange between the models. There is a set of file formats like NetCDF, ASCII, binary and GRIB (ver. 1, 2) which are commonly used by meteorological, air/water pollution and other scientific communities. **NetCDF** (Network Common Data Form) is a set of software libraries and self-describing, machine-independent data formats that support the creation, access, and sharing of array-oriented scientific data (http://www.unidata.ucar.edu/software/netcdf/). The **American Standard Code for Information Interchange** (acronym: **ASCII**) is a character-encoding scheme based on the ordering of the English alphabet. ASCII codes represent text in computers, communications equipment, and other devices that use text (ANSI, 1977). A **binary file** (commonly, but not necessarily, with the extension .bin) is a computer file which may contain any type of data, encoded in binary form for computer storage and processing purposes (http://en.wikipedia.org/wiki/Binary_file). **GRIB** (**GRIdded Binary**) is a mathematically concise data format commonly used in meteorology to store historical and forecast weather data. It is standardized by the World Meteorological Organization's Commission for Basic Systems, known under number GRIB FM 92-IX, described in WMO Manual on Codes No.306. The first edition (current sub-version is 2) is used operationally worldwide by most meteorological centers, for Numerical Weather Prediction (NWP) output. A newer generation has been introduced, known as GRIB second edition, and data is slowly changing over to this format.
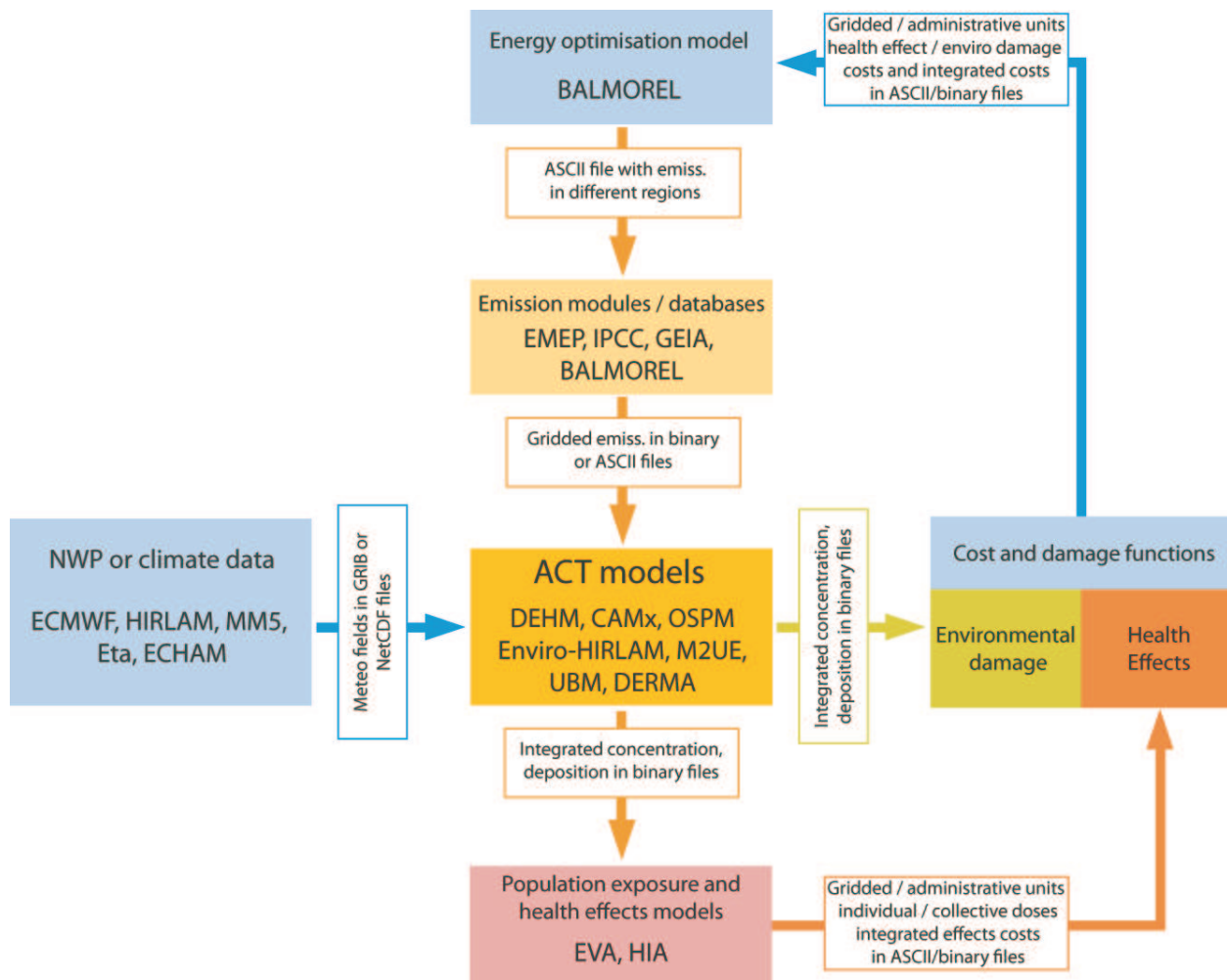
Figure 3.1: Dataflow diagram and input/output file formats in the CEEH model framework

The key elements of the scheme and data flow according to the diagram are described below.

3.2. IO in energy optimisation models

Balmorel does not change the geographical patterns of emissions, but assumes that the existing powerplants can change their capacity and technology used. Emissions (output) associated with the Balmorel investments are delivered to the CEEH emissions module by sectors and regions (in ASCII text-files), which represent the administrative division of Denmark, namely Greater Copenhagen, Zealand, North Jutland, Southern Denmark, Central Jutland (Figure 3.2). The emission sectors are given by SNAP codes (Selected Nomenclature for Air Pollution, Table 3.1). With detailed knowledge of the geographical pattern of emissions and typical stack heights for each sector, the emission output data can be processed for both GIS (Geographical Information System) and lon/lat data formats.
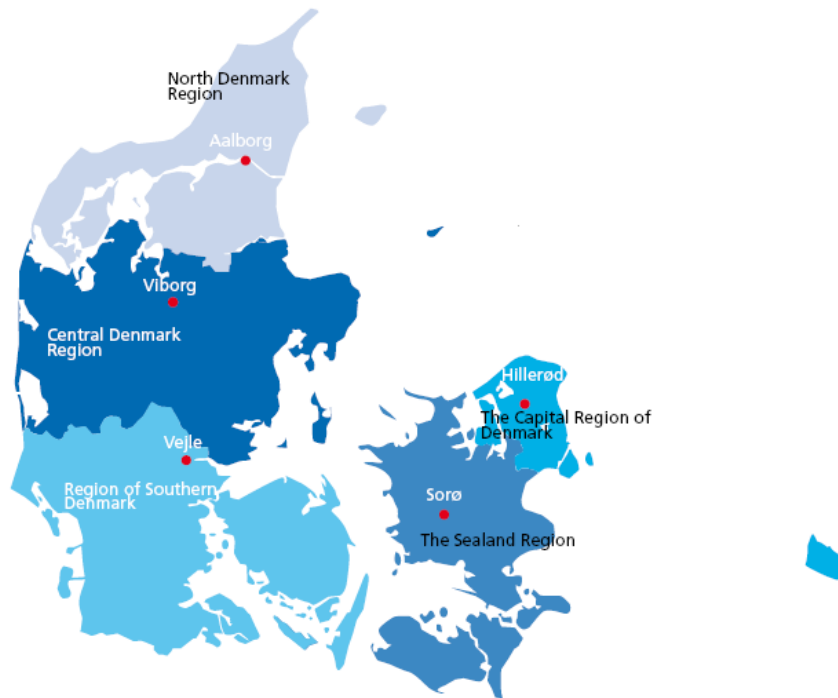
Figure 3.2: Regions of Denmark used in Balmorel model

3.3. IO in emission modules and databases

The Balmorel is divided into regions since the externality costs are likely to be different in different regions. This, however, rises the problem of addressing costs in one area to emissions in another area, which can be handled in the atmospheric chemistry-transport models (ACTMs) by tagging the emission after region and emission sector. The emission sectors are given in SNAP codes (Table 3.1).

Table 3.1: SNAP codes in different emission inventories

a) EMEP emission inventory

Code	Name
1:	Combustion in energy industries
2:	Non-industrial combustion plants
3:	Combustion in manufacturing industry
4:	Production processes
5:	Extraction and distribution
6:	Solvent use
7:	Road transport
8:	Other mobile sources and machinery
9:	Waste treatment and disposal
10:	Agriculture

b) IPCC RCP emission inventory

Code	Name
1:	Surface transportation
2:	International shipping
3:	Aviation
4:	Grassland burning
5:	Forest burning
6:	Solvent
7:	Industry (combustion, processing)
8:	Residential and commercial
9:	Agriculture (waste burning on fields)
10:	Agriculture (animals, rice, soil)
11:	Power plants, energy convertion, extraction
12:	Waste (landfills, waste water, incineration)

In this way the ACTMs have to run one time for each region and each sector. Based on detailed knowledge of geographical location of power plants, stack heights and more, Balmorel emission output data (delivered in regions) will be gridded before input to the ACTM's. From the ACTM's data are delivered to the health effect model in two different formats: In the EVA system, population exposure is evaluated on the grid basis (the EVA system is described in detail in CEEH report No. 3 ,*Brandt et al., 2011),* whereas the HIA model takes in air pollution data on municipality level. After evaluations of costs,data are formatted into cost pr kg pollutant in each region, before they go back to Balmorel. Health costs for different pollutants are assumed to be additive.

It is decided to use the IPCC/RCP 4.5 emission scenario for emissions in the rest of the world. The RCP database (Version 2.0) includes harmonized and consolidated data for three of the four RCPs. This comprises emissions pathways (in NetCDF file format) starting from identical base year (2000) for Black Carbon (BC), Organic Carbon (OC), Methane (CH_4), Sulfur, Nitrogen oxide (NO_x), Volatile organic compounds (VOC), Carbon monoxide (CO) and Ammonia (NH_3). The data provided for the RCPs is extensive - and has undergone several procedures to assure quality and consistency, to harmonize regional base year emissions to recent inventories, and to downscale the projections to 0.5 x 0.5 degree. It was decided to use IPCC RCP 4.5 emission for emission scenarios 2010, 2020, 2030, 2040, 2050. The RCP 4.5 is developed by the MiniCAM modeling team at the Pacific Northwest National Laboratory's Joint Global Change Research Institute (JGCRI). It is a stabilization scenario where total radiative forcing is stabilized before 2100 by employment of a range of technologies and strategies for reducing greenhouse gas emissions. The scenario drivers and technology options are detailed in Clarke et al. (2007).

3.4. IO in ACT models

After a one year air pollution simulation, the following pollutants are given to the health models as annual means: Primary $PM_{2.5}$ and PM_{10}, secondary particles ($PM_{2.5}$) from SO_4^-, NO_3^-, and NH_4^+, and gaseous CO, NO_2 and SO_2. In case of ozone, accumulated peak density and AOT40 are used, respectively, for health impact and environmental impact assessment modelling.

The inputs for some of the ACT models are described below.

DMI models

CAMx

The Atmospheric Chemistry Transport models depend on the applicable meteorological driver as well as selected domain of interest. At present, output (GRIB files) from several nested versions of DMI-HIRLAM (original HIRLAM (http://hirlam.org) model adapted and refined for Denmark) is applied.

An interface between the NWP and ACT models was built, which is based on Perl language and Linux Shell scripts.

Table 3.2 : Data requirements of CAMx

Meteorology (supplied by DMI-HIRLAM) / (UAM-IV binary files)	3-dimensional gridded fields -horizontal wind components -temperature -pressure -water vapor -vertical diffusivity -clouds/rainfall
Air Quality (obtained from either measured ambient data or from large/ regional-scale models) / (UAM-IV binary files)	gridded initial concentrations gridded boundary concentrations time/space constant top concentrations
Emissions (provided by EMEP/TNO/IPCC) / (UAM-IV binary files)	gridded sources elevated point sources
Geographic / (ASCII files)	gridded land use/surface cover gridded surface UV albedo codes
Other (ozone column from TOMS data, photolysis rates from radiative model) / (ASCII files)	atmospheric radiative properties -gridded haze opacity codes -gridded ozone column codes -photolysis rates lookup table
Chemistry parameters / (ASCII files)	chemical information for the simulation and mechanism

CAMx requires various input data to describe photochemical conditions, surface characteristics, initial and boundary conditions, emission rates, and various meteorological fields over the entire modelling domain (Table 3.2). Preparing this information requires several pre-processing and pre-modelling steps

to translate raw data to final input files for CAMx. Chemical mechanisms are already implemented in the model and only the chemical information about the simulation and mechanism has to be given as input.

The produced model output (hourly averaged concentration/deposition of gaseous and aerosol species) is written in binary files. The format of these files follow that defined for UAM-IV concentration files (EPA, 1990).

Enviro-HIRLAM

Since, the Enviro-HIRLAM model (see chapter 2) is based on HIRLAM reference version, the setup of the one is quite similar to the DMI-HIRLAM system except chemistry initialization. So, the following data should be specified in addition to the mentioned above:

- initial concentrations (GRIB/NetCDF files);

- boundary concentrations obtained from either measured ambient data or from large/ regional-scale models (GRIB files);

- gridded emission sources (ASCII files).

The anthropogenic emissions are provided by EMEP, TNO or IPCC. The technique of raw emission data processing is similar to the one described in the section "Emission modules / databases".

The Enviro-HIRLAM output (meteorological and chemical fields) is stored in GRIB format (with minimum time resolution of one hour).

DERMA

The Danish Emergency Response Model of the Atmosphere (DERMA) can be used with different sources of NWP data, including the DMI-HIRLAM and the ECMWF global NWP models with various resolutions (Table 3.3). DERMA is run on operational computers at DMI. The calculations are carried out in parallel for each NWP model to which DMI has access, thereby providing a mini-ensemble of dispersion forecasts for the emergency management.

Table 3.3 : Data requirements of DERMA

Meteorology (supplied by DMI-HIRLAM) / (GRIB files)	3-dimensional gridded fields -wind -temperature -heat flux -pressure -humidity -precipitation -cloud cover -geo-potential
Emissions (ASCII files)	point sources

The produced model output (concentration, deposition with time resolution of one hour) is written in binary and GRIB files.

<u>M2UE</u>

Boundary and initial conditions for the nested M2UE model are used from the CAMx+HIRLAM or Enviro-HIRLAM models. For the boundaries a kind of Dirichlet condition is chosen to provide the values with an interpolation from a coarse to a fine grid. The ASCII input files (each of them contains wind direction and absolute value, turbulent kinetic energy, temperature, pressure, ambient concentrations of gaseous and aerosol species) are read every hour by M2UE.

A computational domain is explicitly defined by buildings, roads, vegetation from high resolution GIS data and Google Earth (http://earth.google.com/). The size of the domain is less than 500 x 500 x 100 m and the grid resolution is around 1-5 m.

A road emission inventory is based on observation data from Danish Road Directorate (http://www.vejdirektoratet.dk/roaddirectorate.asp?page=dept&objno=1024). The model output is written in ASCII and binary files with time resolution of 5 minutes.

3.5. IO in population exposure & health impact and cost & damage models

While output data from ACTMs, which are annual means of pollutant species per area, is on grid, population data used in the health impact models, are on address level or on administrative units, i.e. – not on a grid. For the HIA model, air pollution data are delivered from the ACT models in an excel worksheet with annual mean concentrations in each of 99 municipalities. The geographical municipality data are supplied by Kort og Matrikel Styrelsen (http://www.kms.dk/Produktkatalog/DAGI).

Further data needed from the ACT models are how much of each pollutant in a region is emitted from each of the other regions. These data are not necessarily used by the health impact models but is needed to set up the output from the health and cost model back to Balmorel: Externality cost per kg pollutant emitted in each region (see Section 3.2).

In the first setup of the CEEH model Environmental impact and damage will be neglected, however the environmental damage cost model is under development in CEEH.

Chapter 4. Testing the CEEH modelling chain

Once all the components of the system have been installed it is important to verify in practice that data can be transferred between the different components and that reasonable results are obtained. In the so-called demonstration phase of CEEH, simplified evaluations of externality costs and their effect on the energy system optimization has been performed. This Chapter describes the conditions for different components of the CEEH system in the demonstration phase.

4.1. The demonstration phase simulations and their input data

Following the general modeling framework described in Chapter 1 the demonstration phase simulations uses the following input data:

- **Energy system optimizations including externalities:** With fixed cost values for air pollution and different CO_2 externality prices, Balmorel has been run up to the year 2030, assuming a projected economic development and related energy demand for the time horizon considered. Projected fuel prices for the years 2010, 2020 and 2030 were used in the simulations.

- **Air pollution simulations for the year 2000**. As described in section 2.2, the year 2000 weather has been chosen as input to the NWP driver for all atmospheric chemical transport experiments, including those corresponding to future emission scenarios. Data inventories for background air chemistry and Danish air pollution emissions in year 2000 were used as input to the ACT models.

The demonstration phase in CEEH does not include road traffic in the energy optimization. This will be included at a later stage. Note, however, that calculations of background externality costs associated with road traffic (and other non CEEH sectors, i.e. other SNAP codes) are actually included in the demonstration phase simulations.

4.2. Modelling chain tested

To demonstrate that the system provides plausible results, it has been run for some different case-studies with different basic assumptions. The results presented in the following section are only examples of the kind of results one can gain from Balmorel and should not be taken as the final results from the CEEH:

With reference to the previous sections the demonstration phase simulations includes basic versions of the following main components. Three different demonstration phase experiments were performed:

1. Fixed health costs => Fixed energy system scenarios => Health cost externalities (these evaluations that do not involve simulations, was performed as a contribution to the IDA2050 plan, http://ida.dk/News/Dagsordener/Klima/Sider/Klima.aspx)

2. Fixed health costs + CO_2 externality costs => BALMOREL=> optimized energy systems

3. Inventories for air pollution and background chemistry => DEHM => EVA => Health cost externalities (these experiments are described in CEEH scientific report No. 3, *Brandt et al. 2010*)
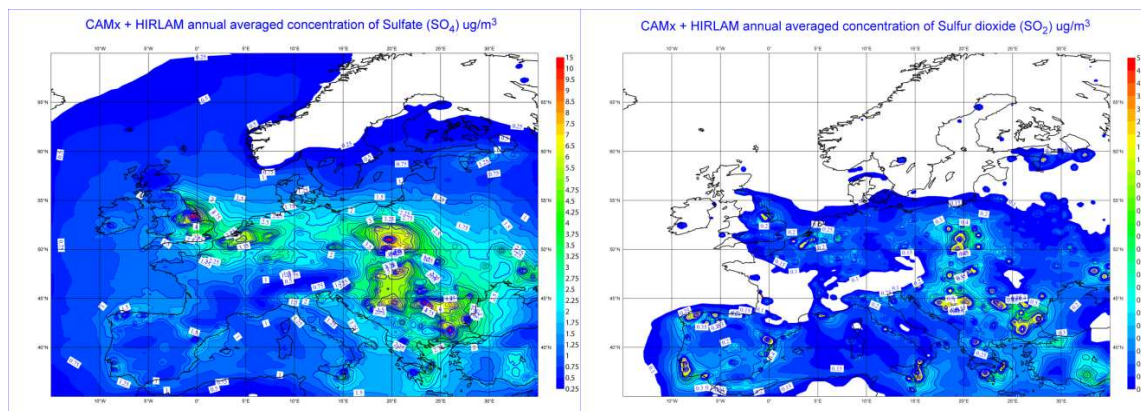

Figure 4.1. An example of simulated annual averaged concentrations of SO_4 (left) and SO_2 (right) for the year 2000 – in this case using the HIRLAM-CAMx v.4 model system.

The fixed healths costs used in the first two experiments come from the third experiment:

Social costs per kg pollution species

DKK/kg	Power	Road	Shipping
$PM_{2.5}$	81	159	Na.
NO_x og nitrat	43	69	80
SO_2 og sulfat	68	243	146
CO	0,00596	0,1639	0,0067

The first experiment is described in detail in the IDA2050 baggrundsrapport

The second demonstration experiment I described below:

The different basic conditions are listed in Table 4.1. The various runs differ according to the assumptions used: no inclusion of any externalities in Run1, different CO_2 costs (10, 25, and 50

EUR/tonne) in runs 2 to 4 together with constant costs for other pollutants, no CO$_2$ charge in Run5, and only CO$_2$ charge of 50 EUR/tonne in Run6. All of them are based on the same fuel prices from WEO 2007 (IEA 2007). For each of the runs Balmorel has been allowed to invest in the various supply technologies to meet the demands in the model domain up to year 2030.

Table 4.1 : Overview of the combination of CO$_2$ cost and inclusion of externalities in the model runs.

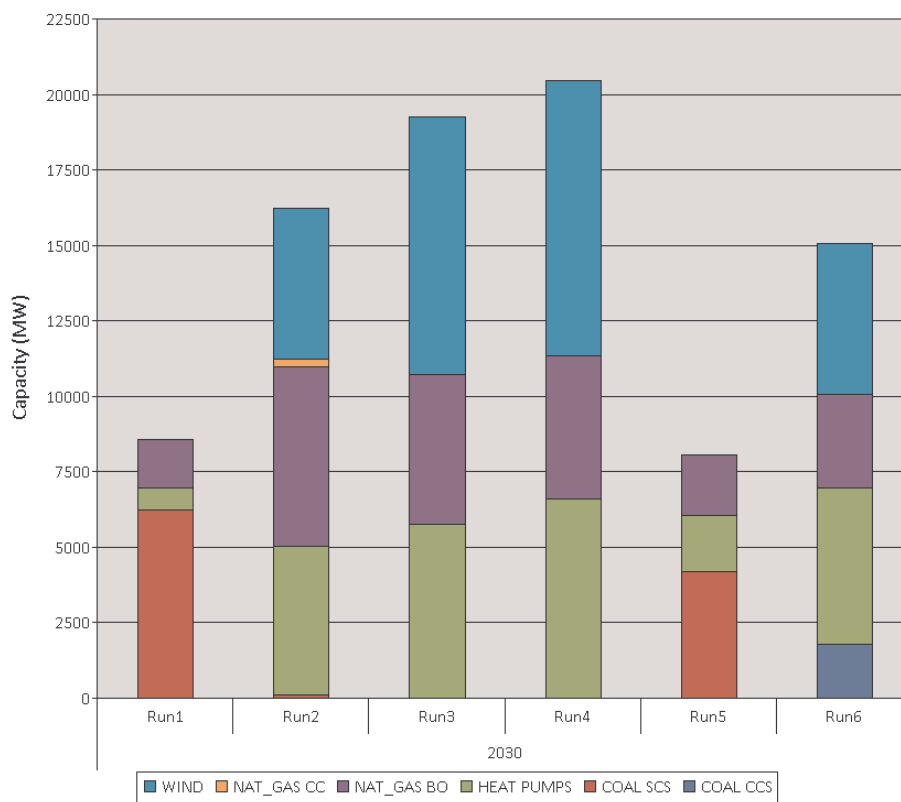|	Run1	Run2	Run3	Run4	Run5	Run6
Externalities	No	Yes	Yes	Yes	Yes	No
CO2-cost (€/tonCO2)	0	10	25	50	0	50

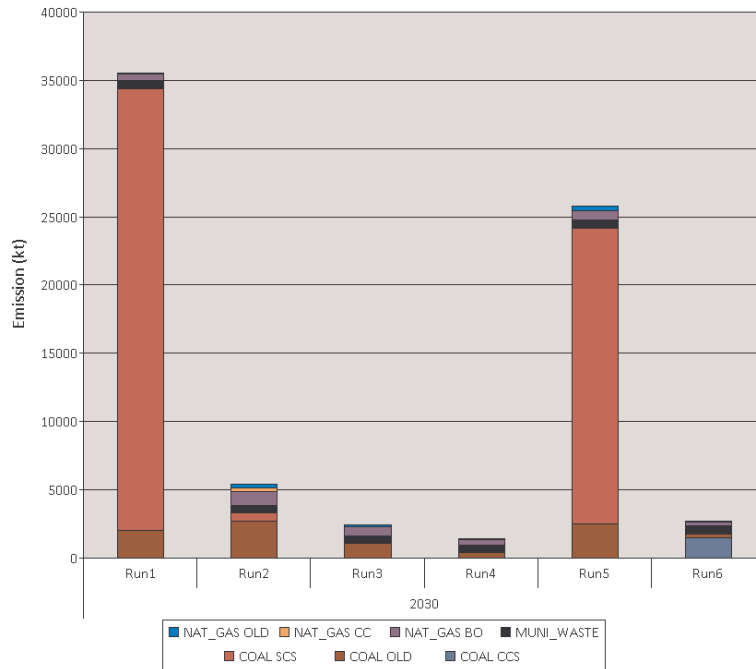**Figure 4.2** : Heat and power generation capacity in Denmark in the simulation year 2030.

4.3. Modeling results

Figure 4.2 shows the distribution of the Balmorel investments in Denmark on different energy sources – here expressed in terms of installed MW[2]. One can see how different technologies are favoured

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[2] Note that Balmorel invests in the entire area shown in Figure 2.3. Therefore – for a given run – the Danish needs may be covered partly from energy sources in the neighboring countries.

depending on the degree to which externalities are included and their corresponding costs. For example, Run1 and Run5 (both do not include any CO_2 cost) contain investments in the coal-based technologies, but not wind. However, directly the opposite is valid whenever the CO_2 charge is in place. In Run6, which is characterised by the highest externality charges even the expensive Carbon Capture and Storage technology is introduced.

Emissions of CO_2 differ dramatically depending on the run (see Figure 4.3). The minimum value achieved in Run4 is approximately 35 times lower than the maximum observed in Run1. Even though no externality cost was assumed for the CO_2 emission in Run5, its level is considerably lower than in the worst case.

Figure 4.3: CO_2 emissions from the heat and power generation in the simulation year 2030 from different fuels.

Comparison of the competitiveness of the technologies for CO_2 cost of 25 EUR/tonne and 50 EUR/tonne is shown in Figures 4.4 and 4.5, respectively. This illustrates why the model chooses to invest differently when externality charges are present contrary to the situation when they are not in place. However, the higher fuel prices and CO_2 cost the less relative influence externalities have on the result.

It should be noted, though, that a large externality cost associated with energy systems is the pollution due to road traffic. This cost was not part of the demonstration phase system. Therefore, once this sector is included, the total investment picture is likely to change significantly.

Even with a moderate CO_2 cost at 25 €/tonCO_2 Figure 4.2 shows that there is no investments in coal power, and wind power and gas are favoured. Together with the investments in wind power there is

also investments in central heat pumps to level out fluctuating power production and to increase flexibility in the district heat and power system. With the high CO_2 cost in Run6 coal power with CCS enters on behalf of gas. The pure impact of the externalities can be seen by comparing investments in Run1 and Run5.

These differences in investments lead to very different emissions of different species e.g. CO_2 as shown in Figure 4.3.

Table 4.2 : Technologies in which investments are allowed in the demonstration phase system.

| Technology	Description	Efficiency	Variable Costs (EUR/MWh)	Fixed Costs (kEUR/MW)	Investment Cost (MEUR/MW)
CC-NG-ENS	Combined cycle nat. gas power plant	58%	0.46	12.50	2.20
COAL-CCS	Coal power plant with CCS	42%	4.80	18.20	1.70
HO-B0-NG	Heat boiler on natural gas	95%	0.67	0.54	0.05
NU-C0-NU	Nuclear power plant	35%	2.20	0	70.00
OC-ADGT-NG	Open cycle natural gas turbine	43%	2.00	32.00	0.50
ST-Biomass-ENS	Biomass power plant	43%	3.10	28.50	1.50
ST-Coal-ENS	Super critical steam coal power plant	48%	2.00	18.20	1.40
WI-offshore-ENS-2	Offshore wind turbine	100%	4.00	18.00	1.40
WI-onshore-ENS-2	Onshore wind turbine	100%	0	15.00	0.80
EH-P9	Heat pump	260%	1.27	3.03	0.32
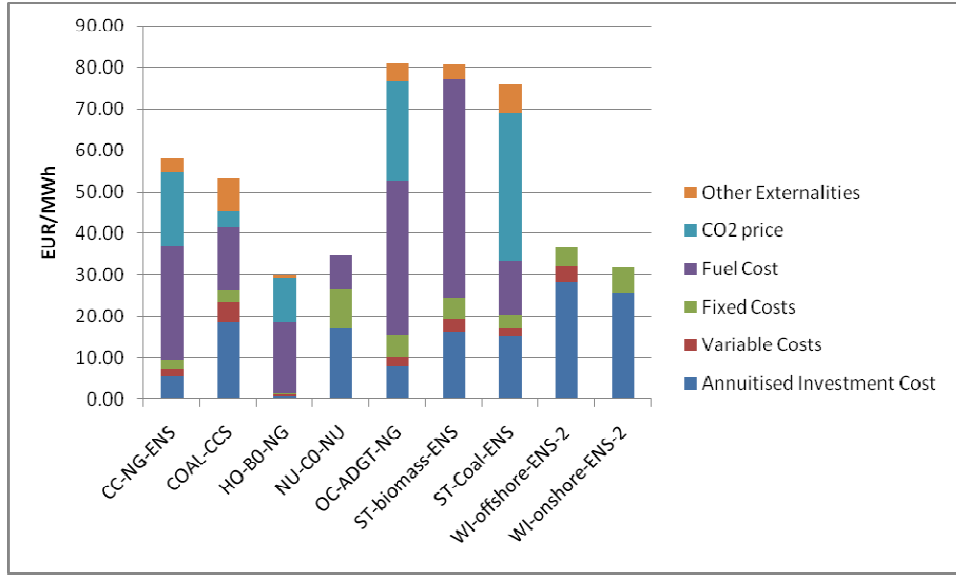
Figure 4.4 : Competitiveness of the possible investment technologies at the CO_2 cost of 50 EUR/tonne.
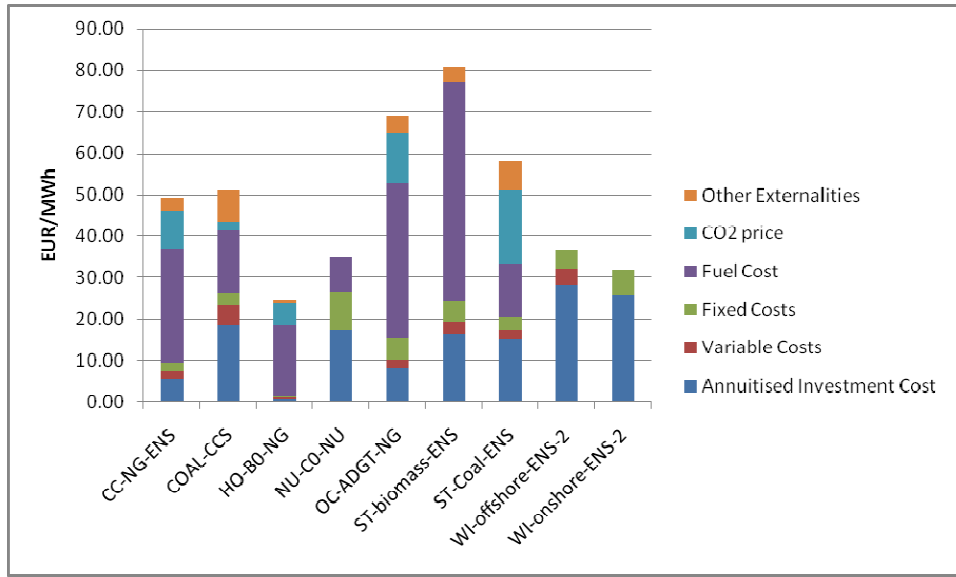

Figure 4.5 : Competitiveness of the possible investment technologies at the CO_2 cost of 25 EUR/tonne.

Conclusions and recommendations

The CEEH scientific report No 1 describes the first phase of the project, where the scientific methodology of the centre is elaborated and combination of modelling tools and data-exchange between models from different science areas has been defined. Some modules are developed in CEEH, while other existing models or modules are improved. It gives a description of the various modelling tools and their mutual interaction in CEEH, supplied with descriptions and results of the first test-runs in CEEH.

The novel and unique product from CEEH is the integrated assessment and proposing of new national strategies for energy production and consumption constrained by economical, environmental and health impacts. This can be used by the government, regional authorities and local administrations, different ministries, industries and other types of decision makers. The results and methodologies developed in the CEEH can therefore also be extended to the European Union and other industrial and developing countries.

In the demonstration phase in CEEH, the various individual models have been coupled together in a way that does not compromise the performance of the individual models. Thereby the CEEH model system makes up a strong tool for accurate measurements of externality costs and energy system optimization.

The expertise in the CEEH framework can validate health externalities in prescribed energy systems, such as the IDA2050 scenarios, using fixed health costs. This should be a standard procedure whenever a future energy scenario is examined.

The ACT models used in CEEH can handle simulations of all emissions in Denmark. They can perform detailed investigations of the air pollution pattern in Denmark, e.g. different sectors and different regions. These details can provide politicians and decision makers with important detailed knowledge about air pollution and its consequences.

Energy system simulations including externalities show that health costs will increase investments in heat pumps, while a CO_2 externality will increase investments in wind energy. These demonstration phase simulations have shown that Balmorel investments in new enegy capacity are very sensitive to the CO_2 externality. It is therefore important to include this externality and to set the value right.

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The Centre for Energy, Environment and Health (CEEH) is a Danish research project, funded by The Danish Council for Strategic Research on Sustainable Energy under contract no 2104-06-0027. The research is executed by an interdisciplinary team of experts with the mission to optimize the future Danish energy systems, taking into account both the direct costs and externality costs to the environment, climate and health.

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5) Description and validation of the CEEH-HIA model

6) Demonstration of the full CEEH chain – the HIA line

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