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Planning of sustainable energy distribution systems
Part I: Problem definition and planning principles

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Part I: Problem definition and planning principles

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RESULT (summary)

This report gives an introduction to socio-economic principles applied to energy system planning in general, but with special emphasis on the planning of local energy systems where more than one energy source/energy carrier are being considered. The following aspects are discussed:

- Energy planning - long term planning of local energy systems
- Socio-economic principles applied to local energy planning
- Possible problem formulations and associated objective functions and constraints
- Use of long term and short term marginal costs in local energy planning
- System boundaries - and corresponding boundary conditions in local energy planning

KEYWORDS

SELECTED BY AUTHOR(S)		
	Local energy planning	Multiple energy carriers
	Socio-economic analyses	Marginal costs

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1 INTRODUCTION

This report represents part I of the results from the R&D project 'SEDS – Sustainable energy distribution systems: Planning methods and models' for the project period 2002 – 2007. The main partners within SEDS have been:

- Department of Electric Power Engineering, Norwegian University of Science and Technology (NTNU)
- Department. of Energy and Process Engineering, NTNU
- Department of Energy Systems, SINTEF Energy Research
- Department of Energy Processes, SINTEF Energy Research

The project has been funded by the Research Council of Norway, StatoilHydro, Statkraft alliance (Statkraft SF, Trondheim Energi, BKK), Lyse Energi and Hafslund Nett, while Norwegian Water Resources and Energy Directorate (NVE) has been a co-operating partner. Our international partners have been University of Porto and INESC Porto in Portugal, Helsinki University of Technology and VTT in Finland as well as Argonne National Laboratory in USA and Swiss Federal Institute of Technology (ETH) in Switzerland.

The main objectives of the SEDS project, as stated in the original project plan have been the two following:

1. Develop methods and models that allow several energy sources and carriers to be optimally integrated with the existing electric power system.
   Particular emphasis is placed on distribution systems and integration of distributed energy sources, from a technical, economic and environmental point of view.
2. Develop a scientific knowledge base built on a consistent framework of terminology and concepts for mixed energy systems, in the field of planning methods and models.
   This will be a cornerstone for the curriculum 'Energy and environment' at NTNU.

Mixed energy distribution systems are illustrated in Figure 1. A mixed energy distribution system means (in this context) a local energy system with different energy carriers (electricity, district heating, natural gas, hydrogen) and a mix of distributed energy sources and end-uses.

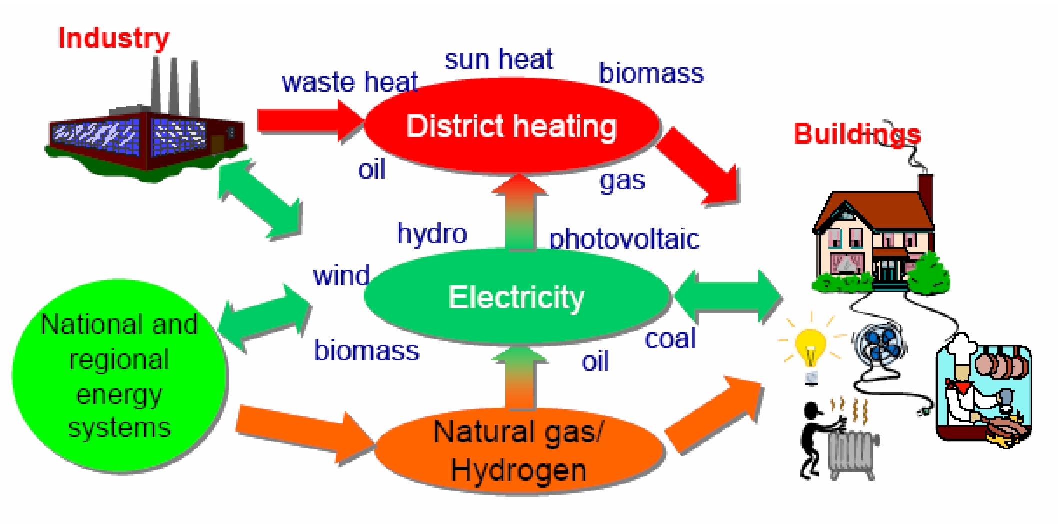


Figure 1 A mixed energy distribution system.

Thus, it is the scientific based methods and models for planning mixed energy distribution systems which are focused in the SEDS project. The term sustainable in the project name should be interpreted in this context. Sustainability relates to all aspects of the recommended planning objective: Economy, quality, security, safety, reputation, contractual aspects and environment. Hence, different energy distribution system alternatives should be characterized with respect to all these objectives, and the planning process should clearly quantify and make these parameters visible and understandable to decision makers and stakeholders, enabling the decision makers to choose sustainable system solutions.

The first objective has been realized through PhD-studies within the following three areas:

- Load and customer modelling of combined end-use (heating, cooling, electricity)
- Quality and reliability of supply in mixed energy systems
- Multiple criteria decision methods for planning of mixed energy distribution systems

In addition an initial study has been performed focusing on environmental impacts using a life cycle assessment (LCA) perspective in planning of local energy systems.

The project has also funded a post doctoral fellowship in multi-criteria decision aid and risk based methodology, and a tutorial given by our partners at University of Porto about risk analysis and multi-criteria decision making.

The second objective has been grouped in two parts:

- Development of a consistent planning framework for mixed energy distribution systems (terminology, concepts, socio-economic principles, general methodology etc)
- Development of a software toolbox environment (web-site) for decision support, visualization and demonstration of methodologies and technologies

For this part SEDS has co-operated with the eTransport project at SINTEF Energy Research [1], where a new tool for planning of energy systems is developed, considering several energy carriers and technologies for transmission and conversion.

The main products from the SEDS project are:

- Technical reports: “Planning of sustainable energy distribution systems” in four parts [1], [14], [15], [16]
- Web-site for energy planning methods and tools [17]
- Three PhD candidates [1]
- Publications in international journals and conference papers [1]
- Presentations at workshops and seminars [1]
- Numerous student project reports and Master theses [1]

The SEDS results constitute a scientific knowledge base for the curriculum Energy and environment at NTNU as well as for energy distribution companies, energy authorities like NVE and governmental agencies like Enova and other stakeholders interested in local energy planning.

[1] eTransport-report: Energy 32 (2007), Elsevier

2 ENERGY PLANNING

The energy system in a country is complex for a number of reasons:

- Dimensionality – the system is nationwide – number of assets and work processes involved is very large
- Number of stakeholders is equally large – the energy system affects everybody, everyday life and all business activities
- Energy supply options (e.g. energy sources and carriers) are multiple and they interact
- Any energy process (conversion, distribution, end-use) has an impact on the local and global environment
- Energy system management has many time horizons – from the microsecond level (e.g. lightning protection) till thousands of years (e.g. nuclear waste storage).

It is impossible to solve the total planning problem in one large operation due to the complexity stated above. Hence energy system planning calls for structured system analysis, simplifications and decompositions.

It is helpful to distinguish between the following planning levels:

1. International level
2. National level
3. Regional (county) level
4. Municipal/ concession area level
5. Part(s) of the municipal level
6. End user level

↕ Local energy system level (levels 4–6)

The **planning objective** (or problem formulation) plays an important role in energy system planning. As the overall energy planning is mainly governed by national laws, regulations and concessions, the national authorities set the framework for energy planning to a great extent. In later years European Directives, for example [9] and [10], also affects the national energy planning framework.

The objective stated in the Norwegian Energy Act [11] is as follows:

§1.2
The act is intended to ensure that generation, conversion, transmission, trading and distribution of energy are rationally carried out for the benefit of society, having regard to the public and private interests affected.

The underlying regulations state that a socio-economic planning approach is relevant to achieve a nation's energy objectives. The planning principles should hence be based on the energy system's contribution to maximize the 'welfare of the society'. In energy planning the main objective is to develop, operate and maintain a socio-economic efficient energy system. The authorities have the responsibility to develop a planning framework (rules and regulations) that gives all stakeholders incentives to move in the right direction.

3 LONG TERM PLANNING OF LOCAL ENERGY SYSTEMS

A part of the overall energy planning regime is the long term planning of local energy systems for stationary use.

- **Long term** is here defined as a planning horizon of 10-50 years
- **Long term planning** is here defined as planning of energy system infrastructure development (investment planning)
- **Local** energy systems mean energy systems on a municipal or concession area level or less

An example of what might be included in a complex future **local energy system** is illustrated in Figure 1.

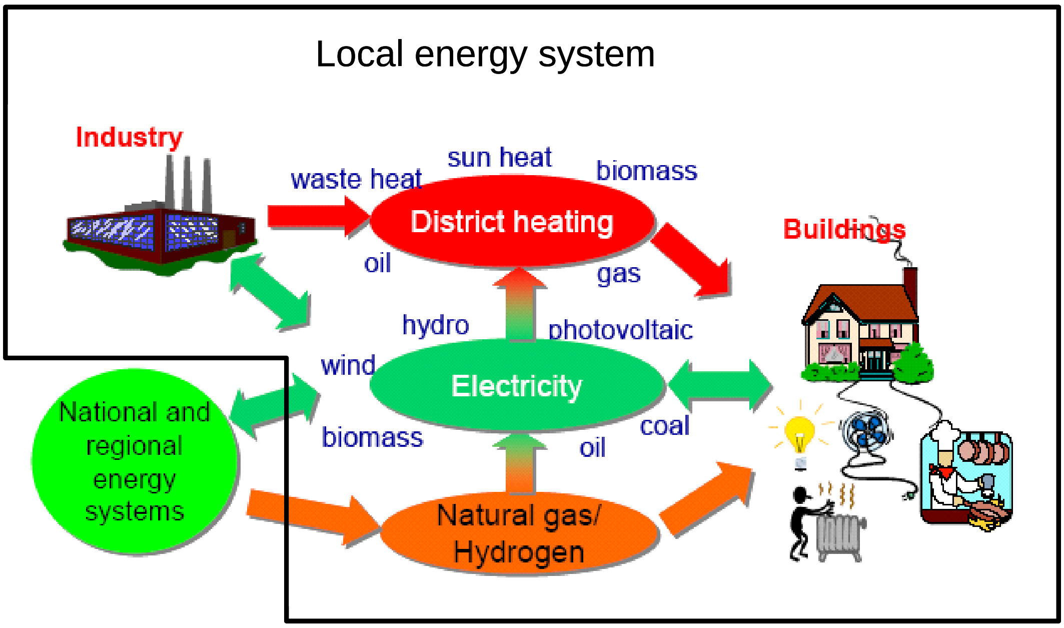


Figure 1 Local energy system.

The local energy system might include different energy carriers (e.g. electricity, district heating, natural gas, hydrogen) and a mix of energy sources and end-uses. As indicated in the figure the different parts of the energy system interact.

The planning phases are in general:

1. Stakeholder identification
2. Problem formulation - establishment of principles, premises and criteria to be used
3. Definition of system boundaries – limiting the planning area
4. Collection of relevant data related to existing infrastructure, demand forecast, available energy options and technologies, costs, restrictions etc.
5. Analyses of relevant alternatives (simulation/estimation of technical, economical, environmental and reputational impact)
6. Decision making (evaluation, negotiation, acceptance etc)

The main stakeholders addressed in this report are the parties responsible for the local energy infrastructure development including their responsibility for the connections of end users and local energy sources and conversion processes – the energy distribution companies. The report has also relevance for the energy distribution authorities especially authorities with roles in planning and concession processes.

The main principles described are also relevant for other stakeholders such as end users and energy providers.

The process of decision making and planning of local energy systems is often subject to a multitude of conflicting objectives. Depending on the decision maker(s) there may be different objectives regarding development of the infrastructure for energy distribution – or at least the weighting on various objectives may vary. The main groups of objectives considered in the SEDS project are *economy*, *environmental impact*, *quality of supply* and *reputation* [1].

4 SOCIO-ECONOMIC ANALYSES – AN OVERVIEW

4.1 GENERAL PRINCIPLES

The overall objective as stated in the Norwegian Energy Act is *to ensure that generation, conversion, transmission, trading and distribution of energy are rationally carried out for the benefit of society, having regard to the public and private interests affected.* This means that the above mentioned decision makers should have a holistic approach, implying that *all costs and impacts* related to the energy system for all stakeholders should be considered, not only those being part of the corporate economics. This objective can be met by applying socio-economic planning principles and analysis.

The main objective of socio-economic analyses is to *explain and make visible the consequences of alternative measures before the decisions are made*. Such consequences include among other things costs that should be charged to public budgets, income changes in private households and business life, and impacts on health, environment and safety. A socio-economic analysis is a way to *systematize* the information. It is important that the investigation of competing alternatives are structured and handled equally. Vital premises for the ranking of different alternatives should especially be made visible.

The following main criteria are important to fulfil in socio-economic analysis:

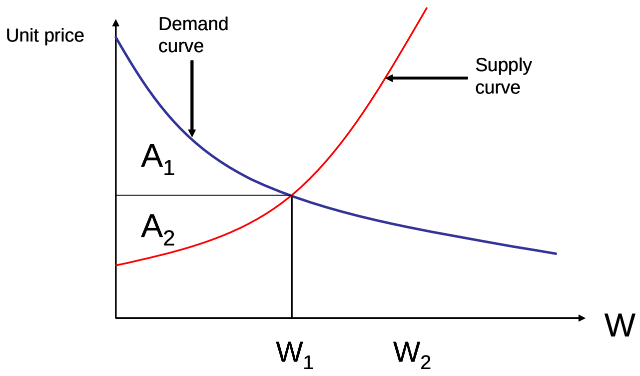
1. All relevant alternatives should be evaluated
2. All relevant impacts of the different alternatives for all stakeholders affected should be included
3. The different alternatives should be compared with the reference alternative which might be the existing system solution (including the “do nothing” solution)
4. It is recommended to seek possibilities for *flexible and robust solutions* with respect to the uncertainties involved and to seek optimal *timing of the implementation*.

In a complete *cost-benefit analysis* all effects are valued in terms of NOK. The values of the Norwegian kroner are used to quantify the importance of the different consequences. Summing up the calculated values of all the consequences, the alternative is *socio-economic profitable* when the sum is positive.

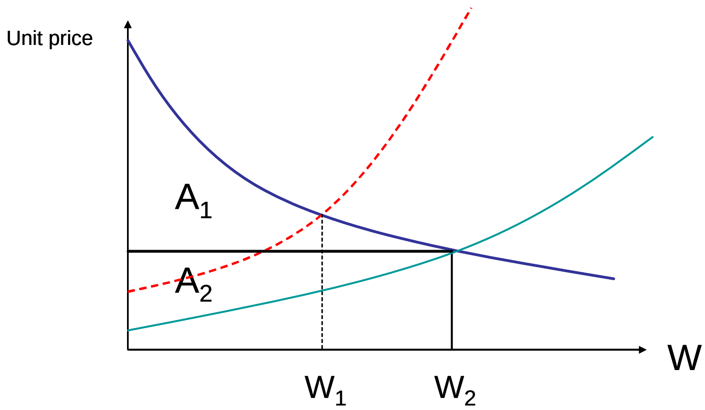
The main principle for the valuation in cost-benefit analyses is that the value in Norwegian kroner of a positive consequence should be equalized by the population’s *willingness to pay for the consequence*. Socio-economic profitability therefore means that *the population together has a willingness to pay at least equal to the actual cost of the alternative*. Even if the total willingness to pay is larger than the total costs, it doesn’t necessarily mean that the alternative is wanted by the society. One of the reasons is that not all consequences can be measured in monetary terms. Another reason is that people also are interested in how the impacts are distributed within the population - which in turn might influence decisions.

Cost-benefit analysis and *cost-effectiveness analysis* are the two most common kinds of socio-economic analysis. In a cost-effectiveness analyses the alternatives are measured only in terms of costs – the benefits are not estimated. This kind of analysis is used in cases where it is not straight forward to value the consequences (benefits) in monetary terms. Cost-effectiveness analyses assume that there exists a given objective for the project and that all alternatives will fulfil this objective with no further benefits. The purpose of cost-effectiveness analyses is to find the alternative that minimizes the sum of the costs by fulfilment of the objective. It is important that other impacts than costs should be described and included in the decision making process and this can be done either by introducing constraints in the objective function (see next paragraph), or to allocate cost attributes to different aspects.

C**ost-benefit analysis** versus **cost-effectiveness analysis** is discussed based on the supply – demand curves shown in the figure below:



a) Demand – supply curve – high supply costs



b) Demand – supply curve – low supply costs

Figure 2 Demand – supply curves.

In a well functioning energy market the optimal energy volume is determined by the crossing point between the energy demand curve and the energy supply curve – see Figure 2a). This crossing point will in principle define the socio-economic optimum. If energy supply is expensive (the red curve in the example) the volume W_1 will be optimal. The socio-economic surplus or measure of welfare is the area composed of A_1 and A_2. A_1 represents the consumers' surplus while the area A_2 represents the producers' surplus. If energy could be provided at a lower cost (the green supply curve in the example), due to so called X-inefficiencies the optimal volume will be increased to W_2. The socio-economic surplus will increase – and in this case both areas A_1 and A_2 will be increased giving both increased consumers' and producers' surplus.

The society's maximum achievable benefit of energy use is in principle equal to the area under the demand curve from zero to "infinity". This is equivalent to the situation that infinite amounts of energy is provided free of charge, which of course is unrealistic. From the society's point of view maximizing welfare gives incentives to make the volume as large as possible. To meet this challenge the energy sector should provide energy at lowest possible cost. The crossing of the supply and demand curve should hence be shifted to the right i.e. to maximize the area under the demand curve. In such a perspective the objective of minimizing overall energy supply costs is consistent with maximizing total welfare. Using the minimization objective the decision maker does not have to estimate the demand curve explicitly, but need an estimate for the expected demand given the established and expected energy consuming facilities subject to expected energy prices.

The local planning objective could then be formulated as: Meet the expected energy demand at lowest possible costs.

4.2 PROBLEM FORMULATIONS – OBJECTIVE FUNCTIONS

In a decision making process certain decision criteria need to be formulated as a tool to choose among alternatives. An objective function is a mathematical formulation of such a criterion.

One definition of the term *objective function* is:

A function associated with an optimization problem which determines how good a solution is.

An objective function is for instance: ***Maximize the total welfare***, which is a consistent formulation with the socio-economic cost-effectiveness analysis previously outlined. The decision model in mathematical terms (objective function) in a local energy planning project (a SEDS project) could be on the form:

$$\text{Max } W = a(\underline{x})+b(\underline{x})+c(\underline{x})+d(\underline{x}) \quad (1)$$

where

- $a(\underline{x})$ - project economics function
- $b(\underline{x})$ - environmental impact function
- $c(\underline{x})$ - quality of energy supply impact function
- $d(\underline{x})$ - reputation impact function
- $\underline{x}$ - vector with decision variables (x_1, x_2,…x_n)

In practical cases it is often difficult if not impossible to evaluate all effects of a project in monetary terms – and different effects although cost-allocated might have a different weight and different uncertainties that make them difficult to include straight forward in an overall total cost benefit objective. To fix unit prices for air pollution (e.g. NOK/kg CO_2) and operating costs for an energy plant (e.g. NOK/kWh) consistently illustrates the problem. To set a price on voltage drop delivered to a customer (e.g. the cost of 230V – 20%= 184V) equally calls for a methodology that is not yet available.

Two different approaches can be used to overcome this difficulty:

- To include certain effects as restrictions in the objective function
- To use a multi criteria approach (multi objective approach when continuous variables are involved – multi attribute approach when discrete alternatives are involved).

So the objective function might be defined in several ways – and some examples are given in the following:

I) Single objective formulation without restrictions:

$$\text{Max}\{f(\underline{x})\} \tag{2}$$

with:

$f(\underline{x})$	- objective function
$\underline{x}$	- n dimensional vector with decision variables

In such a decision model all effects are modelled using a common unit e.g. in monetary terms. In the example the problem is formulated as a maximization problem. If the case is a minimization problem the same notation applies changing Max to Min. In general by multiplying the appropriate objective function with -1 a maximization problem can be transferred to a minimization problem, so the techniques used for problem solving would be the same.

II) Single objective formulation with restrictions:

$$\text{Max}\{f(\underline{x})\} \tag{3}$$

subject to:

$g_i(\underline{x}) \le 0$ $\quad$ i=1,2….m

$h_j(\underline{x}) = 0$ $\quad$ j=1,2….p

with:

$f(\underline{x})$	-	objective function
$\underline{x}$	-	n dimensional vector with decision variables
$g_i(\underline{x})$	-	inequality constraints
m	-	number of inequality constraints
$h_j(\underline{x})$	-	equality constraints
p	-	number of equality constraints

III) Multiple objectives formulation without restrictions

$$\text{Max } \{f_1(\underline{x}), f_2(\underline{x}),\ldots\ldots f_k(\underline{x})\} \tag{4}$$

with:

$f_i(\underline{x})$	-	k objective functions
$\underline{x}$	-	n dimensional vector with decision variables

IV) Multiple objectives formulation with restrictions

$$\text{Max } \{f_1(\underline{x}), f_2(\underline{x}),\ldots\ldots f_k(\underline{x})\} \tag{5}$$

subject to:

$g_i(\underline{x}) \leq 0$ i=1,2….m
$h_j(\underline{x}) = 0$ j=1,2….p

with:

$f_i(\underline{x})$	-	k objective functions
$\underline{x}$	-	n dimensional vector with decision variables
$g_i(\underline{x})$	-	inequality constraints
m	-	number of inequality constraints
$h_j(\underline{x})$	-	equality constraints
p	-	number of equality constraints

The problem formulations could also include integer variables – when some or all x_i are to be integers – calling for special solution methods.

To solve the optimization problem a number of techniques exists from the scientific discipline that is called operations research. The simplex method used in linear programming problems is an example of such a method.

In multi-objective optimization (multi-criteria decision making) given in model III) and IV) the optimization with regard to multiple objective functions is aiming at improvement of all objectives. The goals are usually conflicting so that an optimal solution in the conventional sense does not exist. Instead one aims at e.g. Pareto optimality, i.e., one has to find the Pareto set from which the decision maker(s) can choose a qualified solution (see the example given in Figure 3).

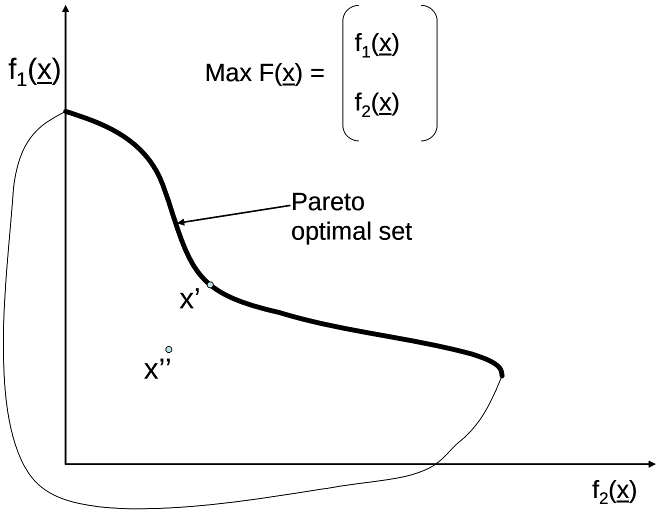


Figure 3 Multi objective optimization – example with two objectives.

The two objective-example in Figure 3 aims at maximizing objectives f_1(x) and f_2(x). The possible states are delimited by the envelope curve and the optimal solutions are indicated by the bold part of the envelope. In the figure it is obvious that the decision $\underline{x}$' is better than $\underline{x}$" although $\underline{x}$' lies in a saddle point of the efficient frontier (also called the Pareto optimal set). The Pareto optimal set are all optimal solutions to the given optimization problem which the decision maker(s) can choose from. One solution on the frontier is not better than another one with this problem formulation.

The objective function can be of a deterministic or stochastic type – the last one including uncertainties i.e. modelling risk. A SEDS objective function including risk could be on the form:

$$\text{Max } W = E[a(\underline{x})+b(\underline{x})+c(\underline{x})+d(\underline{x})] \qquad (6)$$

where

E	-	expectation value
$a(\underline{x})$	-	project economics probability function
$b(\underline{x})$	-	environmental impact probability function
$c(\underline{x})$	-	quality of supply impact probability function
$d(\underline{x})$	-	reputation impact probability function
$\underline{x}$	-	vector with stochastic decision variables (x_1, x_2,…x_n)

This problem formulation considers the decision maker(s) to be risk neutral (i.e. rational).

A more general objective function relevant for risk prone, risk neutral and risk averse decision makers would be to maximize expected utility:

$$\text{Max } W = E[U\{a(\underline{x})+b(\underline{x})+c(\underline{x})+d(\underline{x})\}] \quad (7)$$

where

U - Utility function

A utility function is a measure of the relative satisfaction perceived by the decision maker for different outcomes. Figure 4 below shows examples of utility functions:

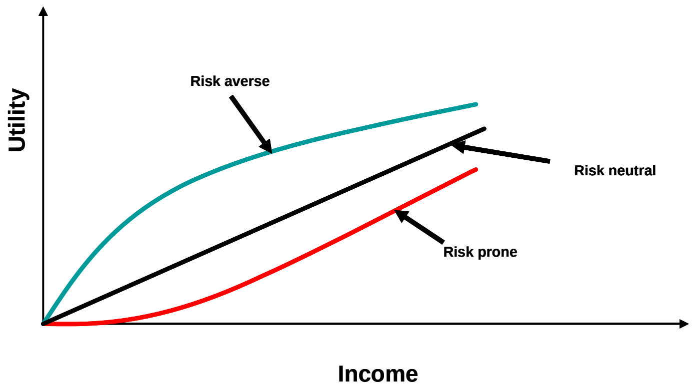


Figure 4 Utility function examples.

The utility function of a risk averse decision maker choosing between different stochastic alternatives will reflect a preference for a more safe outcome with low variance over a more uncertain outcome.

4.3 OBJECTIVE FUNCTIONS – CONSTRAINTS

Figure 5 shows the impact of constraints in an optimization problem. The constraint $x \geq 2$ prevents the solution x = 1 and makes it impossible to reach the minimum of the unconstrained objective function f(x) at x = 1.

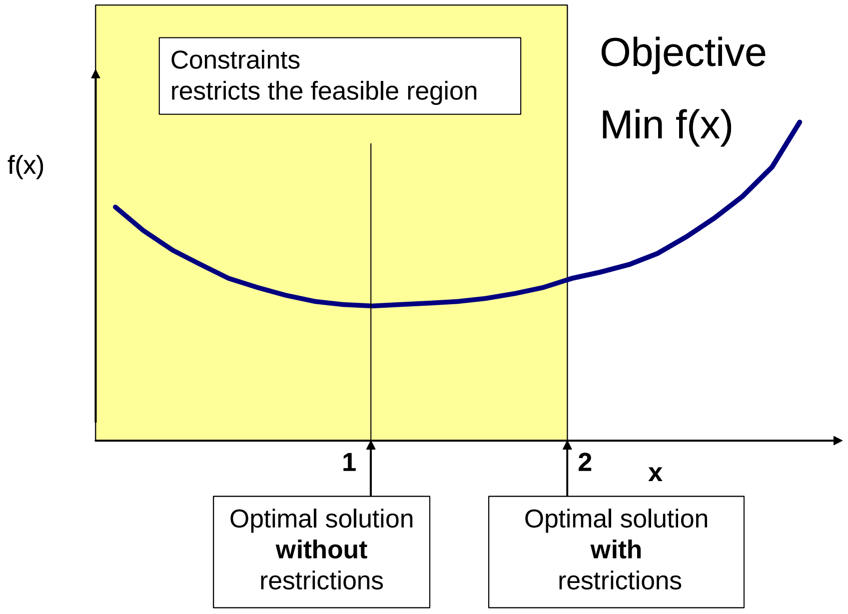


Figure 5 Objective function with constraints.

Such a constraint could also be modelled by adding a ‘shadow’ cost to the objective function. As an example we consider to include a constraint on system reliability – the customer should have less than 5 MWh expected energy not supplied per year. In the objective function we can either introduce this constraint directly or we could include the cost of energy not supplied in the objective function. By setting the unit price of energy not supplied to a certain value, the optimal outcome of the optimization will be a solution with energy not supplied less then 5 MWh. This unit price will be the shadow price of the restriction.

5 SYSTEM BOUNDARIES - LIMITING THE PLANNING PROBLEM

In energy planning different models are used for decision making. As stationary energy systems might be very large, it is often necessary to limit the planning problem to a manageable size as planning resources (money and time) are limited. An important motivation for problem size reduction and hence model reduction, is to reduce data volume and to improve data quality. Result interpretation might also be difficult when the models are very large.

It is hence essential that the planning problem formulation and delimitation is carefully considered when the actual planning process is initiated. To reduce model size, system decomposition is a well known technique. Figure 6 illustrates the principle.

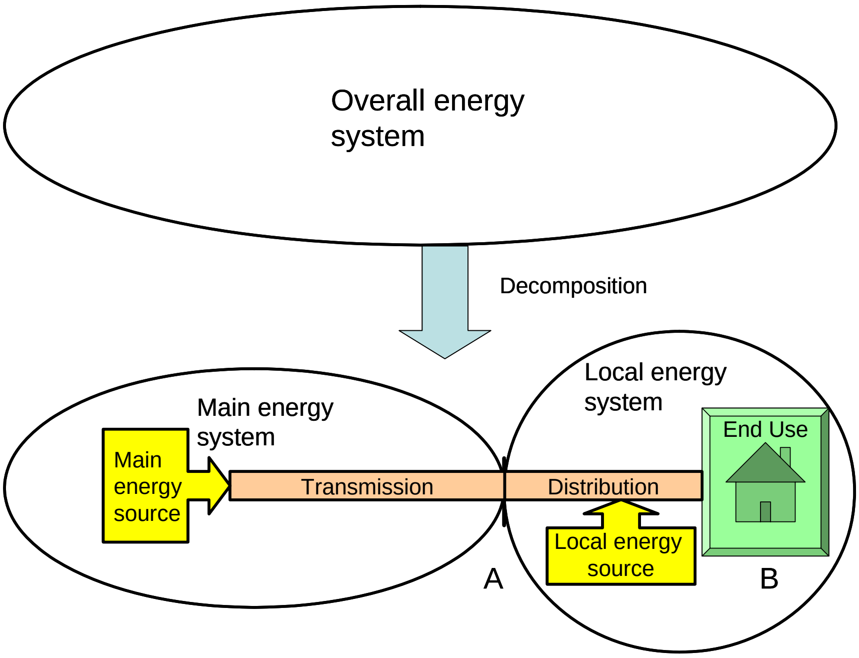


Figure 6 Planning problem decomposition – model reduction.

The overall energy system is divided into two subsystems: The **main energy system** and the **local energy system**. The main energy system is **not** represented in any detail while the local energy system is modelled to the level of detail that the study requires. The main energy system might be the “national” energy system while the local energy system might be a small part of system that should be evaluated. Some examples of decomposition with reference to Figure 6 are given in Table 1.

Table 1 Examples of division in subsystems and system levels.

Study purpose	Main energy system	Local energy system	System level
Installation of heat pump	Electrical power system	Heat pump, building and load parameters (heating requirements, insulation, electrical appliances….)	End user level
Loss reduction in a MV electrical distribution system	Parts of the national power system (generation, transmission and subtransmission system)	Local electrical distribution system (lines, cables, transformers, loads)	Concession area level
District heating to an existing industrial site	Supplying electrical power system	Local district heating system + local electrical distribution system	Part of the municipal level

Establishing system boundaries i.e. where to place the borders between the main energy system and the local energy system is a task that should be carefully considered so that **all relevant effects in the problem formulation are included in the model – and avoiding double accounting of effects.**

In the socio-economic approach, it is a prerequisite that the decisions should be the same as if the whole energy system was owned by one single party. The use of long term or short term marginal costs hence plays an important role in system decomposition. In the following it will be demonstrated that the use of such marginal cost signals contributes to a decomposition scheme that fulfills the single owner criteria.

A very simple model of the main energy system in Figure 6 is to represent it by the costs of delivering energy at the connection point A. This is the most simplified model/representation of the main energy system that can be obtained. The following illustrates that the specific energy cost should be the **marginal** costs of producing and transporting an extra unit energy to point A. The resource allocation (the planning decisions) will then be the same as if the planner undertook the job of modelling the complete energy system shown in the upper part of Figure 6.

As an illustration of the marginal cost principle, it is assumed that the energy customer located in point B requires an annual amount of energy, W [kWh/yr]. The demand is determined by the industrial processes in the customer's facility and is not price elastic. The energy can be supplied from the main energy system or be provided by the local energy system. The local energy system is connected to the main energy system in point A – the alternative of having an autonomous local energy system is not an option in this case. The energy cost function of the main energy system is K_O while the energy cost function of the local energy system is K_L . K_L includes all costs of the local energy distribution system and the costs within the customer's premises.

Total energy supply costs are then given by

$$K_{tot} = K_O + K_L \quad \text{[NOK]} \tag{8}$$

where

K_O	-	Main energy system costs	[NOK]
K_L	-	Local energy system costs	[NOK]

The costs are functions of the generated and transported energy of the different subsystems:

$$K_{tot} = K_O(W_O) + K_L(W_L) \quad \text{[NOK]} \tag{9}$$

where

W_O	-	Main system energy generation and transport	[kWh]
W_L	-	Local system energy generation and transport	[kWh]

Satisfying the total energy demand gives:

$$W = W_O + W_L \quad \text{[kWh]} \tag{10}$$

If the total energy system had a single owner (i.e. a socio-economic approach), the objective would be to minimise overall supply costs while covering the energy demand.

To illustrate the principle we simplify the decision problem to involve only one parameter ’x’. The parameter could be the ratio between local and main energy system generations and transports:

$$x = \frac{W_L}{W_O} \tag{11}$$

The optimal size of x is given by

$$\frac{\partial K_{tot}}{\partial x} = \frac{\partial K_O}{\partial x} + \frac{\partial K_L}{\partial x} = 0 \tag{12}$$

which gives:

$$\boxed{\frac{\partial K_L}{\partial x} = -\frac{\partial K_O}{\partial x}} \qquad (13)$$

By solving (13) the optimal socio-economic value of ’x’ is found.

It is now considered that the two parts of the energy system (the main and the local) are owned by different entities which have a corporate economic agenda. A central question is:

What price signal (tariff) should the owner of the local energy system be subjected to, so that his corporate economic decision concerning the energy ratio ‘x’ will be the same as if the total system was on one hand?

The corporate costs for the local energy system owner K_{Ltot} are given by:

$$K_{Ltot} = k_O \cdot W_O + K_L(W_L) \quad [\text{NOK}] \qquad (14)$$

where

k_O - Specific cost for energy delivered at point A [NOK/kWh]

Minimising local energy system owner’s costs gives:

$$\frac{\partial K_{Ltot}}{\partial x} = k_O \cdot \frac{\partial W_O}{\partial x} + \frac{\partial K_L}{\partial x} = 0 \qquad (15)$$

$$\Downarrow$$

$$\frac{\partial K_L}{\partial x} = -k_O \cdot \frac{\partial W_O}{\partial x} \qquad (16)$$

Comparing (16) with (13) shows that the decision will be the same as in the single owner case if the following equation is satisfied:

$$-k_O \cdot \frac{\partial W_O}{\partial x} = -\frac{\partial K_O}{\partial x} \qquad (17)$$

Modifying (17):

$$k_O \cdot \frac{\partial W_O}{\partial x} = \frac{\partial K_O}{\partial W_O} \cdot \frac{\partial W_O}{\partial x} \qquad (18)$$

$$\Downarrow$$

$$\boxed{k_O = \frac{\partial K_O}{\partial W_O}} \qquad (19)$$

As shown by (19), the correct price signal to reach a socio-economic solution is to set the specific price equal to the marginal costs of withdrawing an extra energy unit from the main energy system.

To have incentives to reach the socio-economic optimal decision, the local energy stakeholder should hence see a tariff that reflects the marginal costs of the main energy system.

Example:
Let the energy cost in the main and the local system be described by the following functions:

$$K_O = k_1 \cdot W_O^2 \quad \text{[NOK]} \tag{20}$$

$$K_L = k_2 \cdot W_L^2 \quad \text{[NOK]} \tag{21}$$

where

k_1 & k_2 - Constants [NOK/Wh^2]

The total energy demand is given by:

$$W = W_O + W_L = \text{Constant} \tag{22}$$
$$\Downarrow$$
$$W_L = a \cdot W$$
$$W_O = (1-a) \cdot W$$

where

a - part of the total energy demand supplied by the local system

What is the optimal distribution of the energy generation in the main system and in the local system? To solve this problem implies determining the optimal value of “a”.

The total energy supply costs are given by:

$$K_{tot} = k_1 \cdot W_O^2 + k_2 \cdot W_L^2 \quad \text{[NOK]} \tag{23}$$
$$\Downarrow$$
$$K_{tot} = k_1 \cdot (1-a)^2 \cdot W^2 + k_2 \cdot a^2 \cdot W^2$$

The figure below shows the energy cost functions:

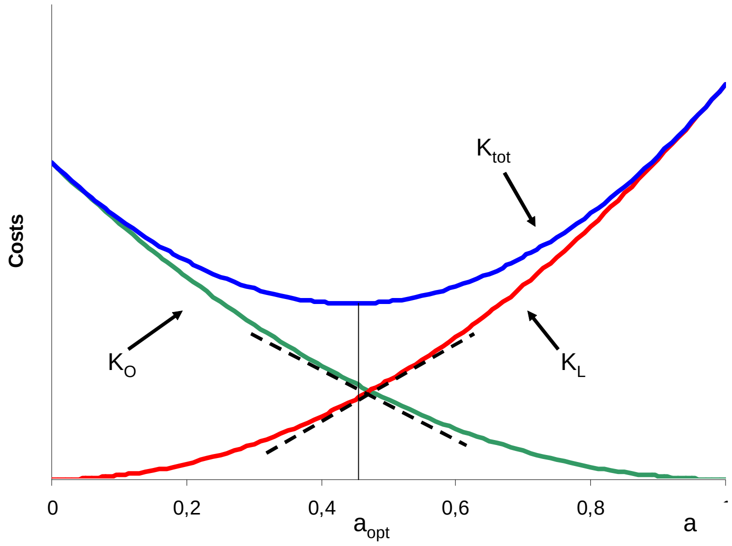


Figure 7 Example Energy Cost Functions.

The optimal value of “a” can be determined as follows:

$$\mathrm{Min}\, K_{tot} = k_1 \cdot (1-a)^2 \cdot W^2 + k_2 \cdot a^2 \cdot W^2 \tag{24}$$

$$\Downarrow$$

$$\frac{\partial K_{tot}}{\partial a} = -2 \cdot k_1 \cdot (1-a) \cdot W^2 + 2 \cdot k_2 \cdot a \cdot W^2 = 0$$

$$\Downarrow$$

$$a_{opt} = \frac{k_1}{k_1 + k_2}$$

$$\frac{\partial K_L}{\partial a} = -\frac{\partial K_O}{\partial a} = 2 \cdot W^2 \frac{k_1 \cdot k_2}{k_1 + k_2} \tag{25}$$

The optimal solution a_{opt} is shown in Figure 7 together with the partial derivatives of the cost functions indicating also visually that requirement given in (13) is fulfilled.

Note that the optimal solution is different from the intersection of the two curves K_O and K_L, unless $k_1 = k_2$ giving $a_{opt} = 0{,}5$.

6 LONG TERM AND SHORT TERM MARGINAL COST

As shown in the previous chapter marginal cost signals are useful tools to optimise energy systems that are owned by different stakeholders. The stakeholders might be energy producers, energy transporters and/or energy users.

Marginal costs might be defined in several ways, but the two most important are

STMC: Short Term Marginal Cost – the cost of loading existing system with an extra unit **without considering** system reinforcement.

LTMC: Long Term Marginal Cost – the cost of loading the existing system with an extra unit **considering** system reinforcement.

Traditionally the marginal cost signals have been applied to expanding systems, but the principle is equally applicable to non-expanding systems or even declining systems.

In the second European Electricity Directive (Directive 2003/54/EC) [9] the marginal cost signal principle is referred to:

National regulatory authorities should be able to fix or approve tariffs, or the methodologies underlying the calculation of the tariffs, on the basis of a proposal by the transmission system operator or distribution system operator(s), or on the basis of a proposal agreed between these operator(s) and the users of the network. In carrying out these tasks, national regulatory authorities should ensure that transmission and distribution tariffs are non-discriminatory and cost-reflective, and should take account of the long-term, marginal, avoided network costs from distributed generation and demand-side management measures.

In the European Gas Directive (Directive 2003/55/EC) [10] the wording is almost the same:

National regulatory authorities should be able to fix or approve tariffs, or the methodologies underlying the calculation of the tariffs, on the basis of a proposal by the transmission system operator or distribution system operator(s) or LNG system operator, or on the basis of a proposal agreed between these operator(s) and the users of the network. In carrying out these tasks, national regulatory authorities should ensure that transmission and distribution tariffs are non-discriminatory and cost-reflective, and should take account of the long-term, marginal, avoided network costs from demand-side management measures.

The following principles relating to pricing and planning of energy transmission and distribution can be identified:

- Fair competition – equal treatment of all customers
- Cost reflective tariffs
- LTMC pointed out as cost/tariff signal
- Non-discrimination of tariffs for distributed generation and end-user measures

To illustrate the estimation of STMC and LTMC, consider the energy system shown in Figure 8 – an energy distribution carrier A-B.

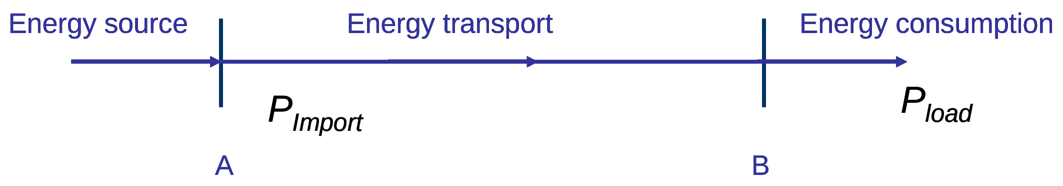


Figure 8 Energy Transport system.

The energy source is the national electricity system and the local demand is so small compared to the total system that the local load will not have any influence on the energy price at point A.

The relationship between the peak power imported and the peak power transported i.e. the peak power delivered at B when considering electricity energy transport is given by:

$$P_{Import} = P_{load} + P_{losses} = P + k \cdot P^2 \text{ [kW]} \tag{26}$$

where

$P_{load} = P$	-	Peak power consumption	[kW]
P_{losses}	-	Peak power losses	[kW]
k	-	Constant	[1/kW]

The constant k is given by the cross section, length and material of the transmission line A-B. The total socio-economic costs involved are:

- Energy consumption costs K_W
- Investment costs (capex) - K_I
  - Including reinvestment and renewal costs
- Operating and maintenance costs (opex) - K_O
  - Including utility repair and damage costs
- Costs of electrical losses - K_{loss}
  - Costs of electrical heat (ohmic) losses
- Customer outage costs - K_{outage}
  - socio-economic interruption costs

Using the cost-benefit analysis approach with a single objective formulation without restrictions (see chapter 4), the energy system is socio-economical optimal when:

$$\text{Min } K_{tot} = K_W + K_I + K_O + K_{loss} + K_{outage} \qquad (27)$$

The cost function for a given capacity (cross section) can be expressed by:

$$K_{tot} = k_W \cdot P \cdot T_{load} + aP^2 + b \cdot P + c \quad \text{[NOK]} \qquad (28)$$

where

P	–	Peak power load consumed at B	[kW]
k_W	–	Specific electricity cost	[NOK/kWh]
T_{load}	–	Load utilisation time	[h]
a	–	Electrical power losses coefficient	[NOK/kW^2]
b	–	Customer outage cost coefficient	[NOK/kW]
c	–	Investment and operating costs for the transport system	[NOK]

Comments:

- The loss coefficient is explained by the fact that electrical losses increase by the square of the current and with a regulated constant voltage it increases by the square of the transported power. If the transported power doubles, the losses quadruple.
- The outage cost coefficient is explained by the fact that energy not supplied to customers increases linearly with the consumed power. If the power doubles the outage costs doubles for the topology shown in Figure 8.
- The peak power situation (P) combined with relevant adjustment factors such as utilisation time for losses, gives a fairly accurate model of annual variations in demand and costs.
- When an electrical distribution system is commissioned, the capex and opex are more or less fixed independent of system load.

Figure 9 shows the total energy and transportation costs for different transport capacities (cross sections) as a function of the peak power demand.

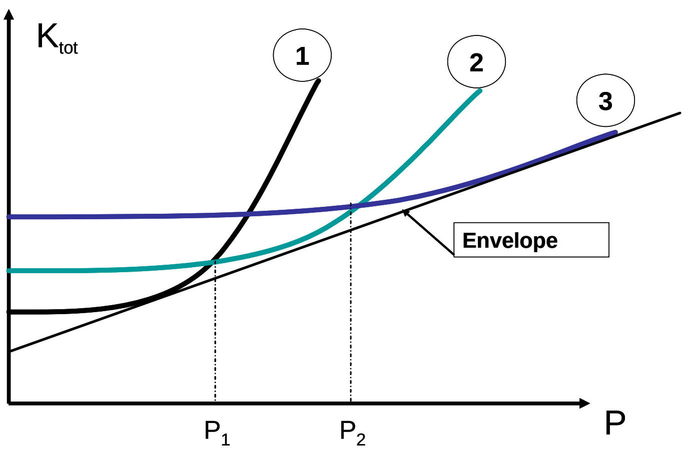


Figure 9 Total Energy System Costs as a function of the peak power demand.

Alternative 1 is the alternative with the smallest capacity (cross section) - with the lowest investment and operating costs (given by the value of curve 1 at P = 0). Due to increase in the cost of losses, the change in total costs increase faster with the peak load for alternative 1 than for those with the larger capacities (2 and 3). This is due to the size of the loss coefficients in (28):

$$a_1 > a_2 > a_3$$

Alternative 1 is the optimal solution when the peak power demand is less than P_1. Alternative 2 is optimal in the interval P_1-P_2. If the peak power demand is larger than P_2 the best solution is to choose alternative 3.

The Short Term Marginal Cost, STMC, at point B for the different alternatives “i” is found by derivation of the different cost functions:

$$STMC_i = \frac{\partial K_{toti}}{\partial P} = k_W \cdot T_{load} + 2 \cdot a_i \cdot P + b_i \tag{29}$$

As the Long Term Marginal Cost, LTMC, considers system investments i.e. optimal system capacity, the LTMC can be approximated by the linear envelope curve shown in Figure 9:

$$LTMC = \frac{\partial K_{tot'}}{\partial P} = k \tag{30}$$

where k is the gradient of the linear curve

STMC and LTMC is shown in Figure 10.

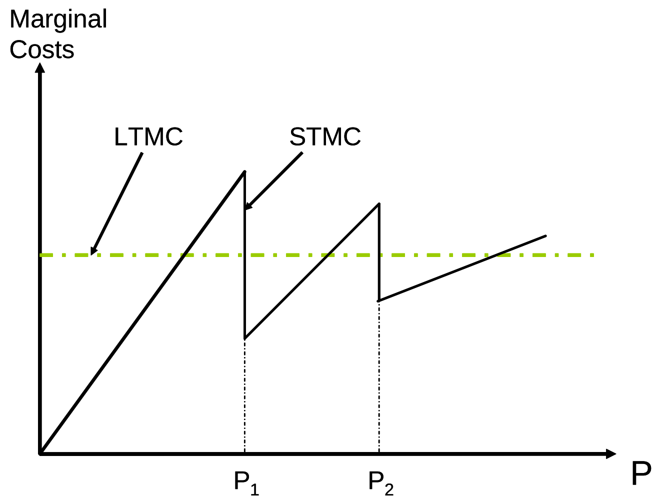


Figure 10 LTMC and STMC as a function of peak power demand.

As shown in Figure 10, LTMC is independent of peak power demand in this example and hence a more stable cost indicator than STMC. This is however not a general fact, but related to the assumptions used in this example.

Figure 11 shows an alternative method/illustration of the difference between LTMC and STMC:

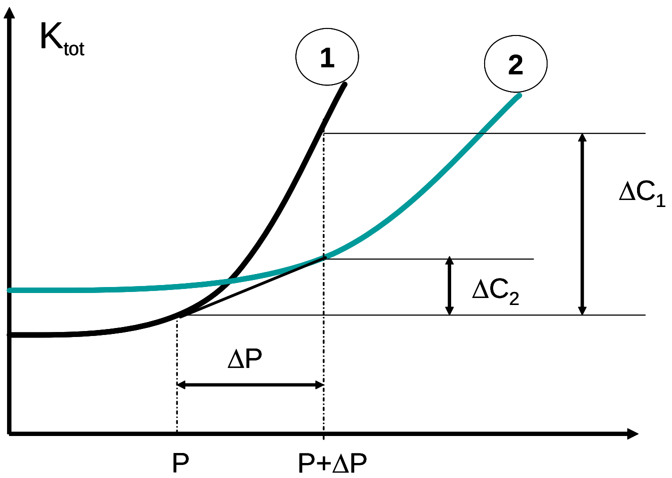


Figure 11 Total costs as function of peak power demand.

The marginal cost signal can be estimated as follows:

$$STMC = \frac{\Delta C_1}{\Delta P} \quad (31)$$

$$LTMC = \frac{\Delta C_2}{\Delta P} \quad (32)$$

As the values will depend heavily on the chosen value of ΔP, the presentation is more of illustrative interest. If ΔP corresponds to the annual increase in peak power demand, (31) and (32) have more practical interest as the cost functions do not have to be established on a mathematical form, but can be based on numerical results from simulations.

When estimating marginal costs, especially long term marginal costs, it is essential which cost elements to include. A risk based life cycle costing approach is deemed to be relevant from a socio-economic point of view. This approach takes into account energy and material flows "from the cradle to grave". The IEC definition *(IEC 60300-3-3 Dependability management – Part 3-3: Application guide – Life cycle costing)* [12] gives the following definitions:

Life cycle costing: process of economic analysis to assess the life cycle cost of a product over its life cycle or a portion thereof

Life cycle cost (LCC): cumulative cost of a product over its life cycle

Life cycle: time interval between a product's conception and its disposal

Including risk aspects (costs) as a part of the life cycle costing approach uncertainties might be included as well. As an example of risk elements in a life cycle costing objective is the Cost of Energy Not Supplied (CENS) in the Norwegian electricity grid regulation.

In the energy industry, risk management is in general drawing more attention due to:

- Market rules are changing
- Uncertainty in regulatory environment
- Competitive pressures are increasing
- Customer expectations are higher
- More major disturbances are experienced and draw media attention
- Increased risk of adverse weather
- Increased supply risks
- More focus on financial risks

To balance all the relevant socio-economic cost (/benefit) factors LCC is considered to be a proper tool.

One option is to base the LCC analysis cost elements on expectation values, i.e. the most probable LCC outcome. A more advanced method is to consider the probability function of the cost elements, transforming the LCC analysis into a risk analysis. As some of the cost elements are rather uncertain (i.e. outage costs, damage costs), a statistical approach is beneficial and more robust.

Performing an energy system optimization for two different load levels W_1 and W_2 by using LCC analysis the LTMC may be estimated as:

$$LTMC = \frac{C_2 - C_1}{W_2 - W_1} = \frac{\Delta C}{\Delta W} \qquad (33)$$

where

C_1 – Optimized LCC at load level 1 [NOK]
C_2 – Optimized LCC at load level 2 [NOK]
W_1 – Load level 1 [kWh]
W_2 – Load level 2 [kWh]

The STMC can be estimated the same principle way, but the cost signals are given by the operational costs which may be estimated by simulation/optimization programs like eTransport, load flow or optimal load flow programs.

7 SYSTEM BOUNDARIES APPLIED TO ENERGY SYSTEMS

The SEDS project focuses on the distribution level, which means the necessary infrastructure for delivering energy to the end-users with integration of local energy resources. The term end-user may here represent a large industrial or public customer or an aggregation of customers to a defined load point in the infrastructure network. Normally, the geographical area is a local area covering for instance a municipality. As discussed in chapter 5 a planning philosophy is needed when the overall energy system is decomposed into a main energy system and a local energy system. In this chapter system boundaries are further discussed.

The decomposition shown in Figure 6 can be performed along several axes:

- Geographical/spatial and technical system boundary
- Energy source – carrier (e.g. separate optimization of the local district heating system from the local electricity distribution system)
- Along the life-cycle (time base) of a project (investment)
- Along the value chain of the energy system (generation, transmission, conversion, distribution, end-use – upstream vs downstream)
- Level of detail (e.g. optimization of transformer size or cross-section of cables or pipes)

The energy sources are several with different properties and qualities - some are renewable, some are not. Utilisation of primary sources will have adverse impacts on the environment – local pollution, green house gases, visual impact, land use disadvantages etc. To make energy sources available an energy infrastructure is needed comprising fuel chains, energy converters, distribution systems, end user equipment to transform energy to energy services. The overall energy system can be compared with the energy process in a large boiler (see Figure 12).

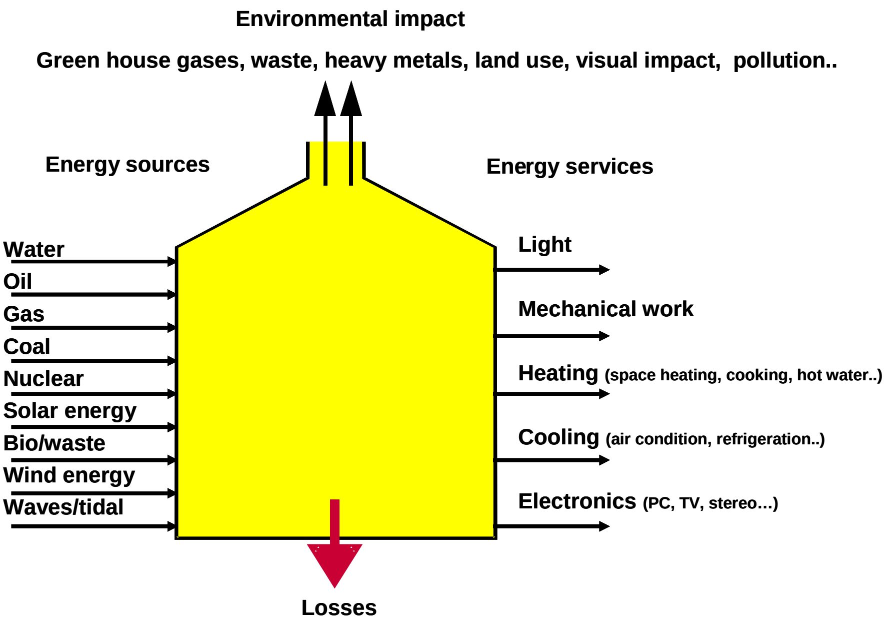


Figure 12 The overall energy system boiler metaphor.

The boiler comprises everything from power plants and oil pipelines to heat pumps, electrical heaters and car engines.

From a local energy planning perspective the same metaphor can be used to illustrate the decomposed energy system – see Figure 13:

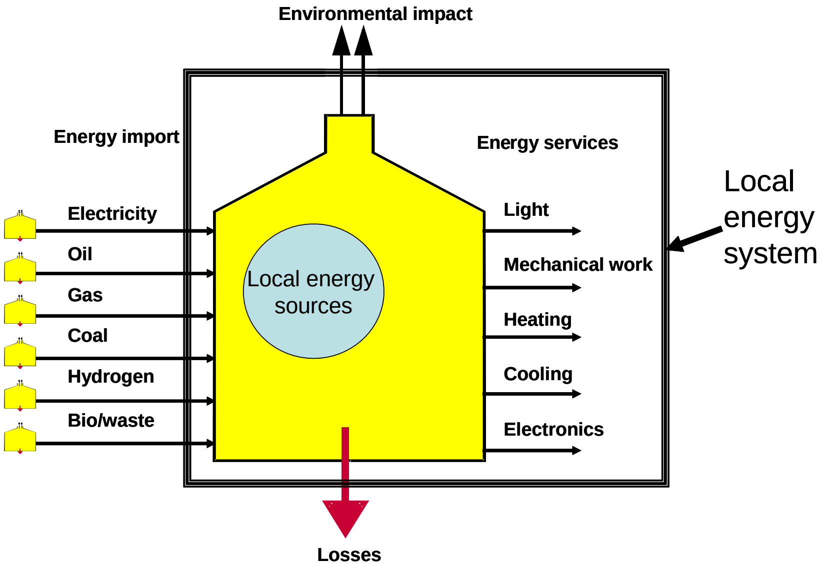


Figure 13 The decomposed energy system - energy service perspective.

As indicated in the figure each energy supply value chain (electricity, oil…) involves a boiler model e.g. energy infrastructure (costs), environmental impact, losses and an energy product with its characteristics. The supply chains might be linked as shown in Figure 2 giving a more complicated meshed structure than the radial structure indicated in Figure 13, but the principle still applies. The illustration given in Figure 13 is energy service oriented. Figure 14 shows the same principle figure seen from an energy customer perspective:

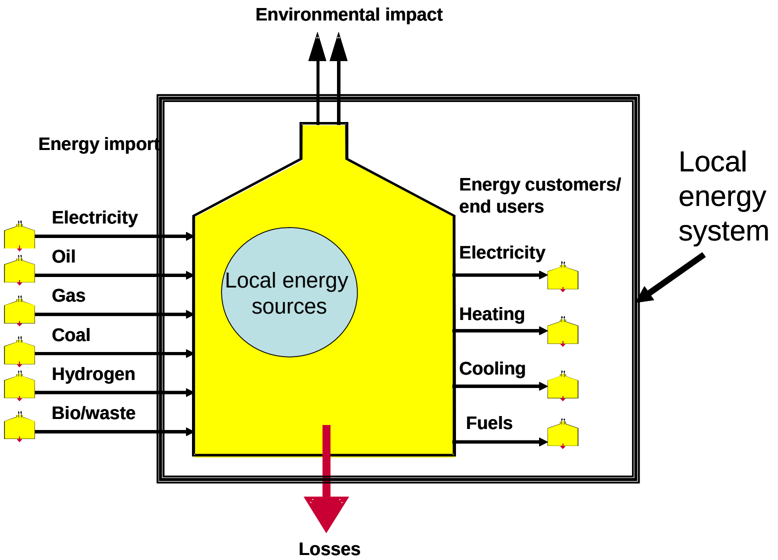


Figure 14 The decomposed energy system - energy customer perspective including customer energy processes.

The planning problem indicated in Figure 14 includes energy customers 'in-house boiler' processes. Such a sub process might for example be the recycling of used worn-out heat pumps.

The system boundary could also be set excluding the energy customer local energy processes – see Figure 15:

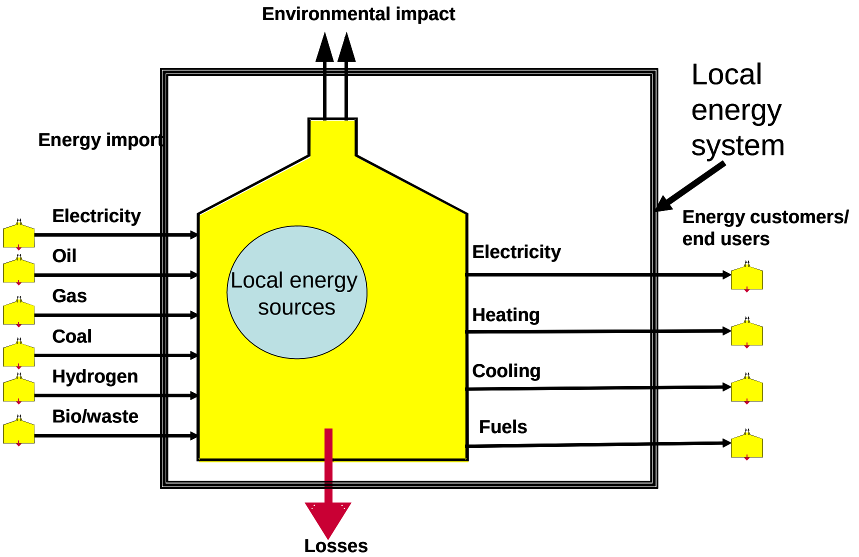


Figure 15 The decomposed energy system - energy customer perspective excluding customer energy processes.

All inputs or outputs of the local energy system reflect boundary conditions that might be modelled in terms of:

- Cost indicators
- Quality indicators
- Environmental indicators
- Reputation indicators

These indicators are in accordance with the SEDS objective. What is important from a planning point of view is that the decision model is socio-economic and holistic in a consistent way to ensure that effects which are reflected in one indicator for one stakeholder is not accounted for more than once. **If the electricity producers have to pay for green house gas emissions and this cost is included in the electricity import price, this environmental impact should not be included as an extra environmental cost in the local energy planning problem.** One could argue that the market price does not necessarily reflect the real costs and actual emissions, particularly when several countries are involved, but even in an imperfect market there is probably no better estimate.

If a multi criteria approach is applied to the local system (within system boundary) one might try to avoid aggregation of criteria into a single economic figure also for the imported energy carrier(s). Then, attributes associated with imported energy carriers should be the same as for locally generated energy carriers in order to make a ‘fair’ comparison of alternatives. Examples of attributes are costs in NOK/kWh, emissions in kg CO_2/kWh, availability indices and possibly energy losses (in case not included in economic terms).

In that case, when generation of electricity or some other energy conversion process outside the local area results in e.g. environmental emissions, such emissions have to be added to the contribution from the local area if they are not accounted for in the import price signal.

In general, from a socio-economic point of view, costs and emissions occurring as a result of decisions made within the system boundaries should be included in the optimisation process. The reasoning above regarding attributes associated with imported energy carriers also applies to considerations regarding the demand side. This means that the infrastructure for different energy carriers on the demand side (end-users premises) has to be included in a socio-economic optimisation.

From a local planner’s perspective it is convenient if all imports and exports are given in terms of market prices that reflect socio-economic costs. It will be difficult for the local planner to have sufficient insight in all upstream and downstream energy value chains to asses relevant cost factors, environmental factors, quality factors and reputation factors if they are not to a certain degree declared by the market and/or by the supplier. In a perfect market the prices will reflect the real costs and the difference between corporate and social economy does not exist, i.e. in a perfect market the socio-economic costs will equal the market price. But in practice this is not always true and should hence be addressed in the specific planning case.

8 REFERENCES

[1] Sand, K.; Holen, A.T.; Kjølle, G.H.; Solvang, E.; Ulseth, R.; Jordanger, E., Catrinu, M.D.:
Planning of sustainable energy distribution systems.
Part II: Planning methodology and tools.
Trondheim: NTNU/SINTEF Energiforskning, December 2007
(TR A6558)

[2] Risnes, A.S.:
SEDS. Gjennomgang av prosjekt- og masteroppgaver i energiplanlegging.
Trondheim: SINTEF Energy Research 2005
(AN 05.12.55)

[3] Wolfgang, O.:
Nettariffer i ETransport
Trondheim: SINTEF Energy Research 2005-07-15
(AN 05.12.111)

[4] Sand, K.:
Grensekostnader i energisystemer – prinsipper og bruk.
Trondheim: SINTEF Energy Research
(Notat, 2004-04-22)

[5] Veiledning i samfunnsøkonomiske analyser (Handbook for socio-economic analyses – in Norwegian), Oslo 2005, Ministry of Finance

[6] Samfunnsøkonomisk analyse av energiprosjekter. Håndbok (Handbook for socio-economic analysis of energy projects – in Norwegian), Oslo 2003, NVE

[7] Veiledning for kraftsystemutredninger (Handbook for electrical power system studies - in Norwegian), NVE

[8] Planleggingsbok for kraftnett (Handbook for planning of electrical power networks – in Norwegian), SINTEF Energy Research

[9] DIRECTIVE 2003/54/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 26 June 2003 concerning common rules for the internal market in electricity and repealing Directive 96/92/EC

[10] DIRECTIVE 2003/55/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 26 June 2003 concerning common rules for the internal market in natural gas and repealing Directive 98/30/EC

[11] REG. no. 959 of 7 December 1990: Regulations concerning the generation, conversion, transmission, trading, distribution and use of energy etc. (The Energy Act Regulations) Ministry of Petroleum and Energy

[12] IEC 60300-3-3 Dependability management – Part 3-3: Application guide – Life cycle costing. Second edition, IEC 2004

[13] Wangensteen, I.:
Power System Economics. The Nordic Electricity Market.
Tapir 2007, ISBN 9788251922005

[14] Holen, A.T.; Kjølle, G.H.:
Planning of sustainable energy distribution systems.
Executive summary.
Trondheim: NTNU/SINTEF Energiforskning, December 2007
(TR A6556)

[15] Sand, K.; Holen, A.T.; Kjølle, G.H.; Ulseth, R.; Jordanger, E.:
Planning of sustainable energy distribution systems.
Part I: Problem definition and planning principles.
Trondheim: NTNU/SINTEF Energiforskning, December 2007
(TR A6557)

[16] Vessia, Ø.:
Planning of sustainable energy distribution systems.
Part III: A life cycle assessment perspective.
Trondheim: NTNU/SINTEF Energiforskning, December 2007
(TR A6560)

[17] Energy Planning Toolbox web-site:
http://www.energy.sintef.no/prosjekt/energyplanningtoolbox/

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