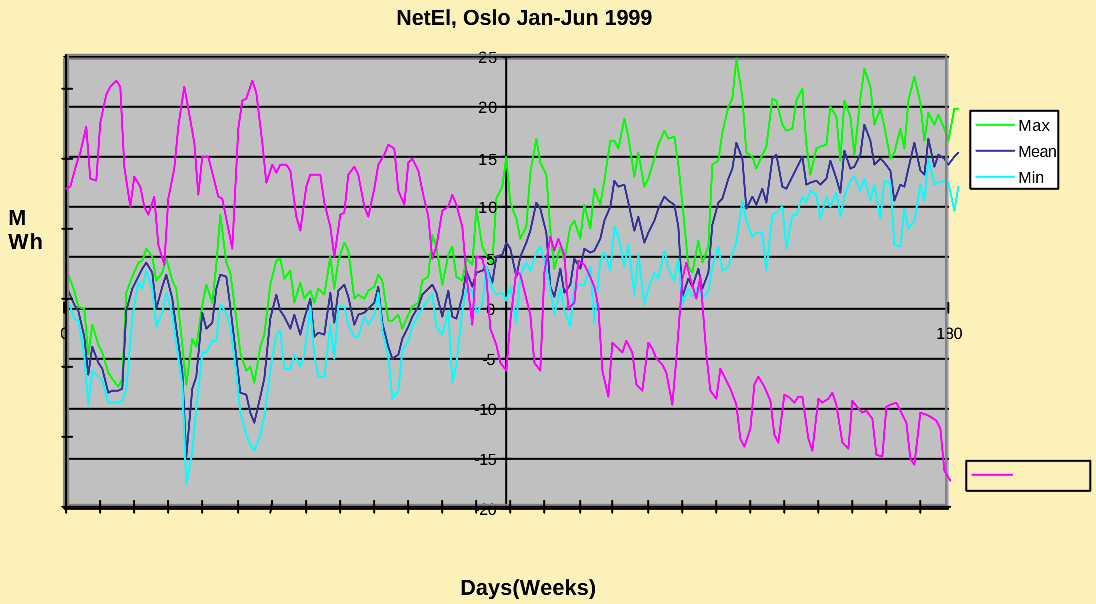
Enviro-cores: A pathway towards more sustainable operation of buildings?



A systems and feasibility study
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SUMMARY

Enviro-cores is a concept for combining heat pumps and thermal storage, to promise a pathway to recovery of much primary energy now used for heating and cooling of buildings. Recovery is by three main mechanisms: taking advantage of any surplus energy, and the more efficient use of primary energy by heat pumps, and seemingly shifting buildings into a climate that is 5-10 ºC warmer (or cooler, as appropriate). In addition, the remaining use of electric power for heating and cooling is shifted away from peak loads. The present report aims primarily to present the concept to an interdisciplinary audience, and to show how energy recovery is achieved.

The "shifting in climate" exploits natural variation in outdoor temperature, to obtain energy in mild weather for use when cold. In order to take advantage of the typical pattern of low pressure passages, a storage capacity of about ten days is required. A water/gravel-based thermal storage with a capacity to deliver 5 kW continuously for ten days requires a volume of 40-50m³, with a temperature difference in the system of some 35-40 ºC. A similar storage using heavy building waste may also be feasible. The temperature difference is obtained through a particular use of the heat pump. The delivered heat comes in addition to any other heat delivered to, or generated in the building, and will meet the demand in typical modern single-home buildings in south-eastern Norway. Row housing, apartments and office buildings require much less, so that single homes form a limiting case.

A shift in climate of 6ºC reduces energy requirements by some 50%. In cooperation with heat pumps and exploitation of surplus heat, two thirds or more of total expenditure seems recoverable. As heat is taken from ambient air, or from the building itself in the case of surplus, the enviro-core concept should be applicable to most existing buildings, as well as to new projects. For new, large projects there may be a situation of competition with heat pump/bore hole technology, and in coastal climates heat pumps alone may suffice.

Work has not progressed far enough to allow any reliable estimates of costs, but as a rough estimate it would seem that the costs of thermal storage and of heat pumps (in volume) may be about equal, and total costs in the order of NOK 100 000.- for a detached house, and perhaps a third for the same space in a modern office building.

PART I: CENTRAL CONCEPTS

1.1 OVERVIEW

Thermal energy storage, heat pumps and optimised automatic operation, which are physically dominating features of enviro-cores, cannot be understood or evaluated in their own right. All have meaning as parts of overall systems, where they act to make these efficient and robust. Discussion and evaluation therefore is meaningful within the context of the combined systems meant e.g. to replace direct heating, the market situation of such systems, and within the overall context of achieving sustainable societies.

In a three-dimensional space of temperature, "geography" and time (cf. section 1.2) there are optima with respect to well-being versus minimal direct expenditure of energy. While ventilation and thermal storage are of ancient origin, and heat pumps are well established modern technology, it is only within the last few years that the realisation has come that their intelligent combination may retrieve significant amounts of energy now expended in operation of our existing body of buildings.

Humans spend much of their lives in and around buildings. Investments in buildings therefore become focal to human health and well-being. This applies as well to investments made for attaining suitable indoor temperature and air quality. In order to prevent loss of heat through draught, modern houses are built almost airtight, with particular vents for air exchange. These tend to be closed in cold weather. The enviro-core concept affords a way to exploit synergy in the combination of ventilation systems, heat pumps and thermal energy storage. Technically, thermal storage involves saving in periods with surplus heat, for retrieval when needed. Furthermore, enviro-cores make available periods of mild weather as a source for renewable energy (cf. section 1.6). As described in the present paper enviro-cores are meant to be used both with new buildings and with existing buildings, where the latter consume the major part of energy on a running basis. The scope of enviro-cores is therefore rather different from concepts intended primarily for new buildings only.

The enviro-core exploits four principal circumstances to "save" energy:

1. *Retrieving heat from outdoor air when mild, for use in cold weather.*
2. *Use/reuse of all energy admitted into the building, including solar energy.*
3. *Saving of surplus heat (cold) for retrieval when needed.*
4. *Allowing heat pumps to operate near optimum efficiency.*

With respect to the first point, a typical pattern of consumption of electric power with variation with outdoor temperature in the Oslo area, is shown in Figure 1.1. The highest required storage capacity in climates like south-eastern Norway, is to last through cold spells of one to two weeks in winter, requiring some 0.2-0.6 m^3 of crushed rock per m^2 of indoor area (depending on insulation and microclimate of buildings). This is some 1/10 to 1/15 of that required for seasonal (summer/winter) heat storage with the same span in temperature, and appear realistic for the required capacities. Sturdy and lasting constructions may be obtained from widely available and cheap materials, to be placed under streets, lawns, parking lots etc..

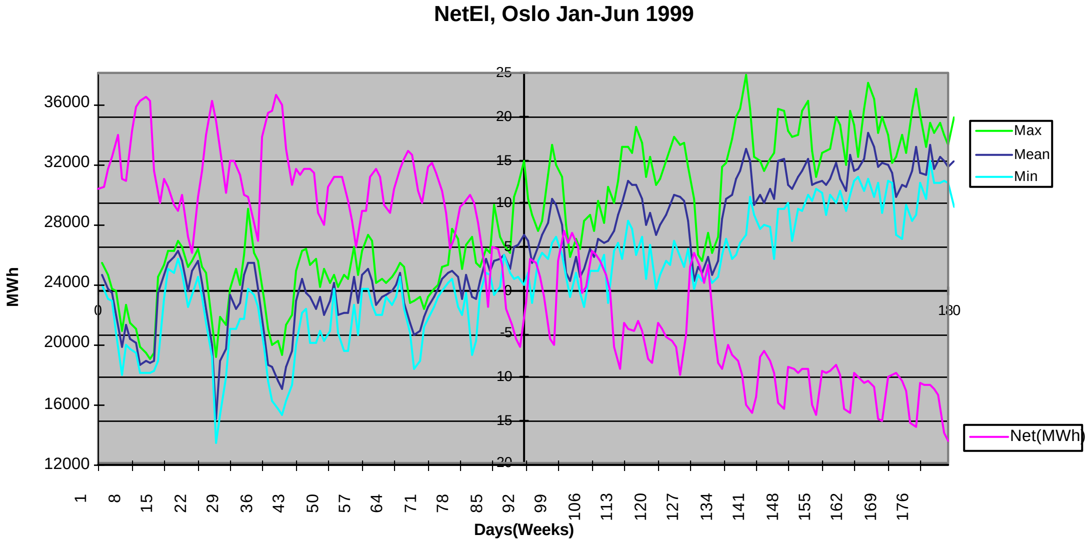

Figure 1.1: *Variation in outdoor temperature and electric power consumption at Blindern, Oslo, spring 1999.*

Figure 1.1 shows three "cold spells" starting at days 4, 16 and 35, with corresponding peaks in consumption of electric power. These episodes last typically 8-10 days. Alternatively, the pattern may be seen as a lower overall temperature, with episodes of mild weather starting at days 14, 27 and 42. Studying the figure in more detail also shows that day/night temperatures stay close up to about day 35, but thereafter there is considerable diurnal variation. Similar patterns are seen throughout the years 1991-1999. The consumption of electric power illustrated in the lower right-hand part of the Figure, shows what consumption is without use of electric power for heating (and additional lighting). With thermal storage available, air at about twenty degrees above the lowest temperature could be used to charge the storage, and with heat pumps this air may be lifted to some 40 ºC for heating purposes. The ventilation system would subsequently make this warm air available where and when needed. Clearly, the process could also take place in such a way that the mild air is first heated and then placed into the storage. The possibility of gaining energy in this way depends on optimisation of operation of the storage of heat, so that ideally the storage is full at the start of a cold period, and almost empty when it gets warmer again. Such optimisation and system control is described in section 1.4. A similar opportunity exists for taking advantage of diurnal (day/night) differences in temperature. These require less of the thermal capacity and are more easily foreseen.

The other principal ways in which enviro-cores "save" energy are simpler, yet more difficult to quantify. Reuse of surplus heat depends heavily on the building's micro-climate, including possibilities for solar heating, and the pattern of use of the building.

1.2 TOWARD CONCRETE OBJECTIVES

Work towards to sustainability touches on a variety of aspects to make it profoundly inter- and multidisciplinary. This is a main challenge in bringing concepts like the enviro-core to practical reality. It is easier to handle if one are confronted with concrete objectives (like "Man on the Moon"). On this background it is proposed that work to develop enviro-cores assumes concrete targets:

- *Recovery of 20-25 TWh of "green energy" within the next 20 years in Norway*
- *Reduction of fossil fuel CO2 emissions from buildings by 3 million tons within the next 20 years*
- *To achieve this with well ventilated, comfortable and healthy indoor environments*

It is assumed for these targets that the overall picture of energy supply does not change drastically from what exists today. If evaluation work now going on comes out as hoped for, it should be possible to specify a schedule with concrete targets:

- *An initial research programme for verification and modelling*
- *Building of an instrumented pilot installation*
- *Building one or more benchmark installations to prove the system and obtain practical costing experience*

1.3 PRINCIPAL INTERACTION OF THERMAL STORAGE, HEAT PUMPS AND VENTILATION

We stated in section 1.1 that enviro-cores take advantage of synergy between heat pumps, thermal storage and ventilation. Each of these factors may be viewed as a dimension in a three-dimensional space. Within this space there are areas that are optimal with respect to suitable indoor temperature and air quality, combined with minimum use of high-quality energy. The term "energy" as used here, corresponds to the technical term *exergy* which denotes energy that may do physical work (cf. section 1.4). Exergy may be used to move energy in the form of heat from a lower to a higher temperature, where the amount required is:

$$Q \bullet f \bullet (T_2 - T_1)/T_2 \qquad 1.3a$$

where

Q = The amount of heat transferred
f = a friction coefficient (> 1.0)
T_1 = start temperature (ºK)
T_2 = final temperature (ºK)

As heat is moved from one thermal mass to another, the overall outcome is one thermal mass (say air) at a lower, and another at a higher temperature, compared to the situation at the outset.

This operation is in principle carried out by *heat pumps* for both heating and cooling. For heating the amount of air brought to a higher temperature may be a factor 2-6 times what it would be if the same amount of exergy was used for direct heating. This *coefficient of performance* (COP) depends on the difference in temperature involved according to 1.3a, on thermal and mechanical friction in the equipment, and on thermal losses throughout the system. In sum, heat pumps provide us with a dimension of temperature in which to optimise.

Thermal storage in a similar way provides a dimension of *time*. The value of this becomes clear when we inspect situations like Figure 1. Without thermal storage there is no time-dimension; all opportunities for increased energy efficiency becomes restricted to what we may achieve then and there. With thermal storage we may take advantage of knowledge of the past, and of regularities in patterns in the micro-climate and the use of buildings.

The third principal ingredient is the moving of heat from one physical location to another, which we have placed under the hat of "ventilation". This is physically accurate to the extent that heat is moved by means of air, but we use the same terminology to describe the situation of where heat is transported by means of a liquid (normally water) and subsequently transferred to air by means of heat exchangers.

Based on this principal approach to the interplay between thermal storage, heat pumps and ventilation, we may search for optima. The object function for this search will relate energy gained to costs, subject to robustness, durability and ease of operation.

1.4 FUNDAMENTALS OF THERMAL STORAGE

Thermal energy storage is superficially a simple concept. Any object contains an amount of heat (often designated "Q") that is the mass of the object multiplied by its specific heat (normally designated "c"), and the absolute temperature of the object (T_1). If the object is in contact with a second object at a different temperature T_2, then heat will flow from the warmer to the colder object. The overall amount of heat to be transferred between two objects is:

$$Q = c \bullet m \bullet (T_2 - T_1) \qquad 1.4a$$

where:

T_2 = the higher temperature

c = specific heat
m = mass.

The flow of heat may do some useful work, returning the exergy:

$$E_x = Q\bullet(T_2\text{-}T_1)/T_2 \qquad 1.4b$$

Heat measured through equation 1.4a is referred to as *sensible heat*. Heat may, however, also reside in various physical and chemical circumstances, with the result that it may be transferred into (or out of) objects without their temperature changing. Examples are the conversion of ice to water, or water to vapour. Heat in this form is called *latent heat*. The basic concept of thermal storage is to place heat into a (sensible or latent) heat store, for later retrieval. In this, losses are involved in heat transfer and in all kinds of leakages of heat from a higher to a lower temperature. Also, some exergy is required in order to transport heat (move a mass) from one physical location to another, although with well-designed systems this is a small part of the total.

The general way of transporting and storing heat is by means of a fluid (air or water) that is either brought into contact with a solid mass, or the heat is stored in the fluid itself (water). In the first case there exists a situation as shown in Figure 1.4:

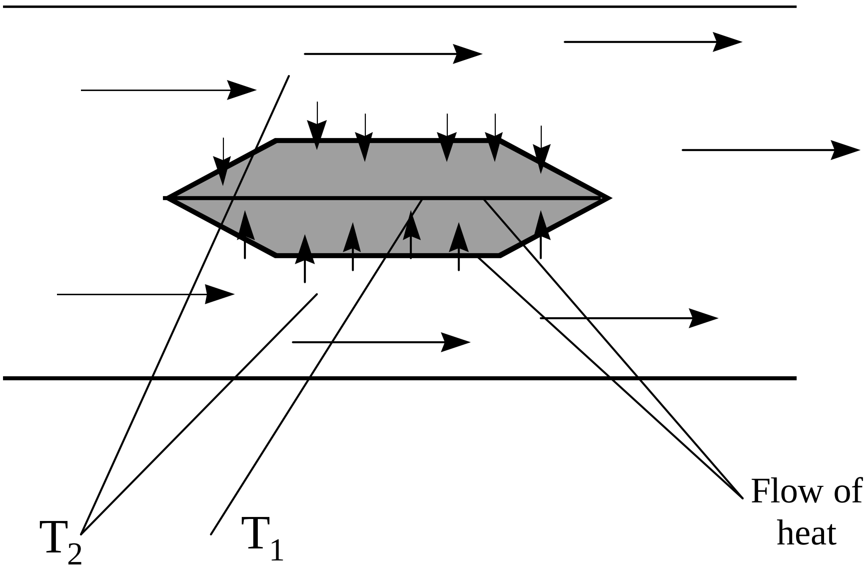

Figure 1.4: *Transfer of heat as fluid moves past a solid body*

When T_1 in Figure 1.4 is equal to T_2, heat will flow both ways at the same rate, with equilibrium as an overall result. If T_1 is lower than T_2 then heat is stored in the solid body, and the other way around releases heat from the body to increase the temperature of the fluid. There is an evening out in temperature due to resistance to thermal transfer that becomes noticeable when the time between shifts in temperature in the fluid becomes comparable to the time for reaching equilibrium between solid and fluid. This problem is avoided when using liquid water both as the fluid and as the heat storage medium, as the water may then simply be pumped back and forth, without any need for heat transfer into or out of a solid. When gas (air) is used as the fluid, then a solid is required to store heat as the specific heat of ideal gases is about one thousandth that of, say, stone.

The final concept that we need to look into is heat transfer. This is generally described by:

$$Q = A \bullet (T_2 - T_1) / (1/h_F + d/h_S) \qquad 1.4c$$

where:

A = available area
T_2-T_1 = temperature difference
h_F = heat transfer coefficient from fluid to solid
h_S = heat transfer coefficient of solid
d = radius (thickness) of solid body

Heat transfer from fluid to solid (or reverse) is thus proportional to available area, to difference in temperature and to heat transfer coefficients for fluid and solid. It is inversely proportional to the thickness (size) of a solid body.

The basic properties for design is:

1. *Heat capacity is proportional to volume of core (volume times specific heat)*
2. *Heat transfer rate is proportional to cross section of flow*
3. *For a given core volume, flow resistance is inversely proportional to the third power of the cross section.*
4. *There is an upper limit to rate of transfer of heat for two-phase systems, determined by transport of heat into/out of individual particles (cf. Figure 1.4).*

1.5 CONTROL AND OPTIMISING

The main feature that sets enviro-cores apart from traditional approaches is the control and optimising inherent in the concept. The basic task of controlling indoor temperature is divided into two distinct features:

1. *The supply of heat (or cooling) to users*
2. *Optimising the amount of energy that a given installation may provide, given the properties and use pattern of the building, its micro-climate, and the weather conditions at large.*

The first feature is under the control of individual users essentially as they now control traditional systems, namely by turning heating devices up and down. When turned down, an enviro-core system may automatically switch to cooling (i.e. the system may begin to accumulate heat in the thermal storage). The regulation by users may also directly involve ventilation.

The second feature is completely transparent and invisible to the individual users. Depending on the degree of filling of the thermal storage (determined by means of the position of its temperature gradient, cf. section 1.7), current weather forecast, the microclimate of the building, current outdoor temperature, time of day, day in week and time of the year, and energy use patterns in the past, the system will seek to achieve an optimal balance of heat and cold in the storage. In particular it will seek to take advantage of natural variation in outdoor temperature, as this is seen in Figure 1.1. The algorithm to achieve this is not as complex as one might initially expect. It is also capable of including new parameters, and new patterns of behaviour, as this might be requested through future development. We now turn to a description of this algorithm.

To start with, a system has its highest potential for providing energy when it is full. Thus during winter when the building needs a net influx of energy, the target for optimisation is to keep the system as well charged as possible. In summer an opposite situation exists, and the system seeks to accumulate cold in the same way. In spring and fall there is an intermediate situation where the system seeks to maintain the thermal storage about half full.

With respect to the algorithm, we note that any enviro-core system will consist of valves and throttles, fan and pump motors, and heat pumps, that are either turned on or off, or set to a limited set of intermediate positions (¼ open, ½ open, ¾ open etc.). Likewise the storage is empty, 20% filled, 40% filled and so on, and present temperature is much below, below, at, just over, or much over that expected for the time of the year. Equally, the wind is from a few specific directions, it is overcast, partial sunshine or clear skies, and so on.

Each of these conditions may be represented by a "one" in a given position in a memory field in a computer; which otherwise is set to zero. Each such field represents a state description of the enviro-core and environment of the building, and how it is expected to develop within the next week or so. Similarly, any particular setting of the enviro-core system may be represented by "ones" and zeros in a similar memory field, so that such fields represent system states.

We may now for each of a set of environment states, work out sensible ("as good as possible") ways the system should act, in terms of whether heat pumps should be running, the storage should give off or accumulate energy and so forth, and we may associate each environmental state with as corresponding system state. In this way we end up with a two-column table of environment states and corresponding energy-optimising system states. Our remaining task is to associate a current environment situation (in the form of a current environment state description) with a system state that is as optimal as possible. The current environment state is determined by suitable readings of temperatures and settings of other parameters e.g. from the weather forecast. We associate the current environment with the best matching environment state, and thereafter obtain the (optimal) settings from the associated system state. Finding the nearest environment state is as follows:

Any environment state consists of some set of ones and zeroes. We consider such representations as equivalent to numeric values (numbers), and place the state fields in numerical order. A simple search in this ordered list will retrieve the environment state description that best matches the current state. We may not have an environment state description that fully matches the current one, but we will find the closest one available. In order for this to work, we must position the individual settings (the position of zero/one for each given parameter) in such a way that the most important ones comes to dominate the sorting procedure. It may be that we may need several different tables of matched environmental states/system states in order to handle diverse operational conditions. Whether or not this will be required awaits further investigation and practical experience.

The algorithm as described here will come up with a (fairly) optimal specification for a system state; e.g. the settings of individual valves and motors etc.. If implemented on an ordinary personal computer, the latter will have a "card" that will set control voltages correspondingly. The required state tables and software will load ordinary personal computers minimally, and may easily run as background programs on such computers. Similarly, now straightforward software is required in order to obtain meteorological data over the Internet, but it is only in the last few years that this has become practical.

1.6 ESTIMATE OF GAINS

The purpose of this section is to present estimates of "saving of energy". This seemingly simple concept is not as simple when looked into in more detail. However, the overall outcome is that electric power and fossil fuels become available for other use or may serve a larger mass of buildings. The gains are basically economic by way of saved fuel and avoided investments in the distribution grid, and environmental in reduced emission of pollutants. The gains come in several different forms.

1. *Shifting of peak loads*
Perhaps the best known advantage from thermal storage is to shift load away from periods of peak demand. This is so in particular for nuclear plants and high efficiency coal fired plants, neither of which handle varying loads well. Norwegian hydro plants are much more amenable to varying loads, but even here the grid must be dimensioned for peak loads, so that costly investments in transformers and power lines may be avoided if loads are spread. Also, losses are proportional to the square of the current density ($w = r * I^2$), so that higher losses arise from a given amount of

energy delivered as uneven peaks. This form of advantage is hard to quantify, and will be realised only as thermal storage apply to a reasonable part of total load. The gains from a more even supply situation will primarily accrue to the companies operating the grid system.

2. *Save for a rainy day*
A second type of "saving" with thermal storage is achieved as it becomes possible to store heat in periods of surplus for later reuse. The alternative is to vent off surplus heat and use "new" energy for re-heating as required. The saving will clearly vary with buildings and with use of buildings. Likely situations for gaining energy in this way is to transfer heat into the thermal storage at the end of the workday, reduce temperature and losses during the night, and then quickly reheat the building in the morning by means of the stored energy. Similarly, solar heating and higher outdoor temperatures during daytime may be taken advantage of. In warm climates, lower temperatures at night may be similarly exploited. As with shifting of peak loads these are gains that are difficult to quantify, but may be substantial.

3. Synergy with heat pumps
A third type of gain is associated with the use of heat pumps, also as integrated in enviro-cores. The "saving" here consists in more efficient use of electric power. There are two different kinds of contributions. The first is the contribution that comes from the heat pumps as such. This is obtainable without any thermal storage. However, the efficiency of heat pumps decreases with the difference between outdoor and indoor temperature, and as commonly installed are not effective below -10 ºC. Heat pumps "on their own" are particularly appropriate in coastal climates, or where some source of heat (e.g. sewage or ground water) may be tapped. Within this regime they will recover about 60% of the power that would be required with traditional resistance heating.

4. *"New" renewable energy*
The second way heat pumps will contribute, is to work in synergy with thermal storage. This opens for the possibility to lift the temperature of outdoor air in mild weather, and subsequently to store this heat for use in cold weather (and the other way around for cooling). To gain an immediate understanding of how this works, and the approximate gains that may be achieved, we look again at Figure 1.1. We see (cf. also section 1.1) that there are three periods of cold weather starting in early January, and with mild weather in between. These periods of mild weather are connected with low pressure weather systems passing over southern Norway. Consumption of electric power during the cold spells soars to some 36000 MWh/day at this particular supply station, while it is about 30000 MWh/day with outdoor temperatures around 0ºC. From the right-hand side of Figure 1.1 we see that consumption of electric power when there is little or no heating, is about 18000 MWh/day. Figure 1.6 below show the same set of data with a polynomial fitted to show the direct relationship of power consumption to outdoor temperature.

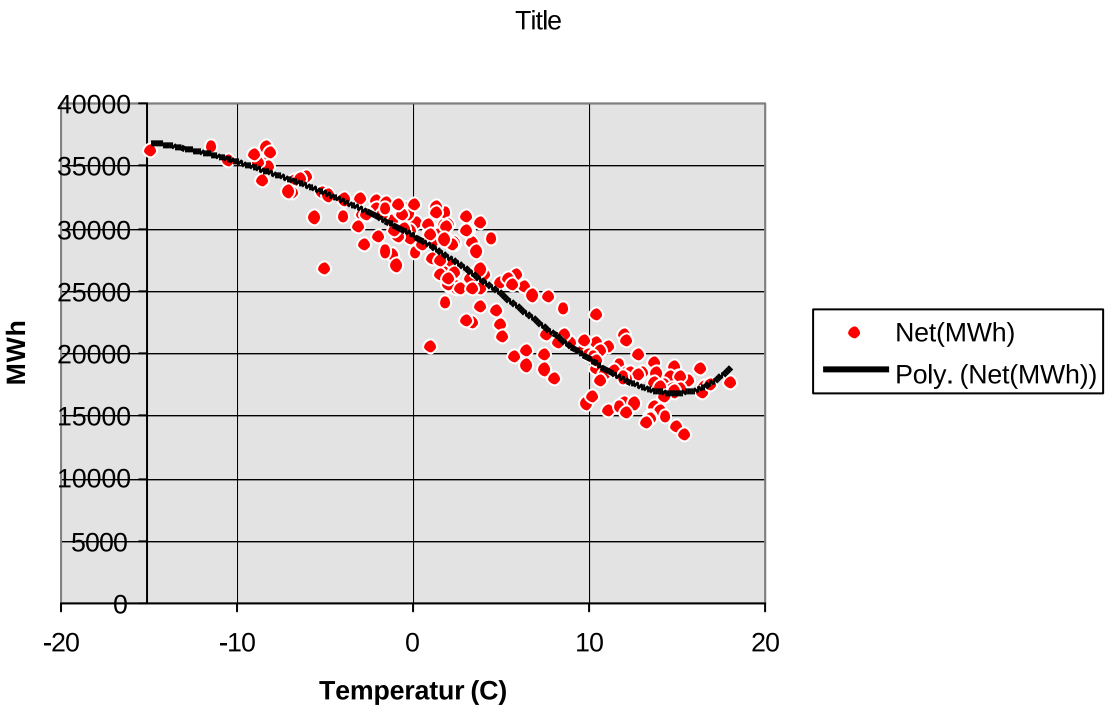

Figure 1.6. *Relationship between power consumption and outdoor temperature* (data corresponding to Figure 1.1)

At the steepest part there is about 4% increase in electric power demand for each degree lower outdoor temperature. The curve flattens out as the temperature goes below about - 5 ºC, presumably because other heating (fossil fuels and firewood) takes over.

If we charge the thermal storage in the mild periods shown in Figure 1.1, and make the heat available during the cold spells, the overall effect is to lift the outdoor temperature by some 15º, implying a saving of some 60% of the energy used for heating in these cold periods (we assume that the heat to be replaced in a building is proportional to the temperature difference, other things equal). The cold spells take up some 60% of overall time, leading to overall reduction in demand for electric power of some 35% in January in this concrete case. If the fossil fuel heating is reckoned in, then a reduction of some 50% is indicated. As Figure 1.1 is followed into spring, the diurnal variation becomes dominant, providing an overall lifting of outdoor temperature of some 6-8º. The corresponding reduction in demand is by the reasoning above, some 25-35%.

On the other hand, the optimisation discussed in section 1.5 will not be perfect. We assume here some 70% of optimal recovery, and there is further losses from thermal leaks and in heat transfer. These are, however, counteracted by the other types of gains discussed above. In addition comes the gains from heat pumps proper. Data from the years 1991-1998 from the same geographic location indicate the same pattern. This particular location consists of residential areas, the University of Oslo and a major hospital. Also, clearly, it reflects the climate in Oslo. Lower gains would be expected in coastal climates like the west coast of Norway, and higher gains in continental climates like those in the central parts of southern Norway and also e.g. in much of Sweden.

The above way of estimating gains as a fixed percentage is made for pedagogical reasons. It is conservative. A much more sophisticated approach is used professionally to evaluate the requirements for heating and cooling of buildings, as outlined in the attached report by Mathisen et al (2003). This approach is based on the concept of *balance point temperature* and "degree-day" calculation. The balance point temperature is:

> *"The balance point temperature of a building is defined as the value of the outdoor temperature at which, for the specified value of the interior temperature, the total heat loss is equal to the heat gain from the sun, occupants, lights, and so forth."*
>
> ASHRAE Fundamentals 2002

In quantitative terms:

$$t_{bal} = t_i - (q_{gain}/K_{tot}) \qquad 1.6a$$

where

t_i = Indoor temperature
q_{gain} = Total heat loss equal to heat gain from sun, people etc.
K_{tot} = Total heat loss coefficient for building (in W/ ºK)

In simplified calculations t_{bal} is assumed constant. Mathisen et al (2003:9 (Figure 14)) give a relationship between balance point temperature and "Kelvin days" that indicate a reduction in heat requirement for a building, of some 50% when t_{bal} is reduced from 13ºC to 7ºC, i.e. by 6ºC. In practice, t_{bal} varies throughout the day (Mathisen et al, 2003:8), and calculations are performed by computer-based models. Such modelling has thus far not been carried out with respect to enviro-cores, but is seen to provide a much more detailed and solid basis for estimates of gain. As far as the work has now reached, we conclude that about 50% of the energy now used for heating of buildings, would be recoverable through widespread installation of enviro-cores in the existing building mass.

PART II: SCENARIOS FOR PRACTICAL IMPLEMENTATION

This part is concerned with the practical construction of enviro-cores. The main effort has so far been devoted to the practical construction of thermal storage facilities, and how these may be integrated into complete systems. Major categories of implementation relate to the medium used for heat transfer (air or water), and to how warm and cold zones are formed and kept apart. A wide variety of thermal storage solutions are described in the literature, as extensively reviewed by Dincer and Rosen (2002). Among the most popular solutions are tanks containing water. However, for stores like those required for enviro-cores such tanks are relatively expensive, and are sensitive to leakage. Also, there are problems with stabilising separate zones of heat and cold, and particular reinforcement is required to allow loads on top, e.g. for parking. The work described here has instead focused on storage facilities constructed from heavy building waste or crushed rock. Heavy building waste consists mainly of crushed and graded concrete and bricks. It is interesting because construction of storage facilities on this basis presents a way to use such waste for something useful. It now creates disposal problems particularly in cities and built-up areas (Oslo Kommune et al., 1999). Also, a disposal fee typically of some NOK 100.- / 150.- ton of waste helps to reduce costs of construction.

While crushed rock does have a direct cost, it is durable, plentiful and cheap materials. Compared to water tanks both crushed rock and heavy building waste have the distinct advantage of giving constructions that are geophysically stable without reinforced walls, and that will carry loads. Also, they help to stabilise thermal zones. On a dry basis these materials have volumetric specific heats about one third that of water. If graded and soaked in water this increases to about half that of water.

2.1 MAIN CATEGORIES OF STORAGE SOLUTIONS

The principal operation of a thermal core is shown in Figure 2.1a:

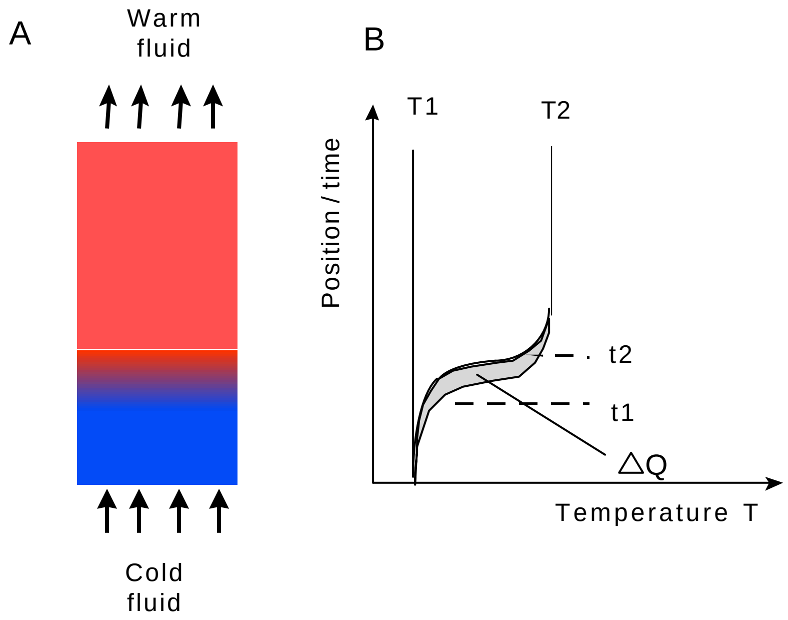

Figure 2.1a. *Principal operation of a thermal core supplying heat.*

The amount of heat ΔQ given off in a period of time Δt is shown as the shaded area in Figure 2.1a/B. This corresponds to the movement of the transition zone between the cold and the warm part of the core. The actual output from the core is a given amount of heat transfer fluid at a particular temperature (typically 40 ºC). Charging of the system takes place by just reversing the direction of flow of the transfer fluid.

Air or water is used as transfer fluid. The fluid either percolates through the porous core, or particular channels or tubing are used. With percolation a chromatographic distribution principle serves to keep warm and cold zones apart, and creates a thermal transition zone. For this to work, flows must be slow enough to allow thermal equilibrium between the circulating fluid and individual pebbles. The distribution of heat between the stationary and the mobile phase determines how fast the transition zone will move. This in turn is determined by the respective heat capacities (mass times specific heat). With circulating water the capacity will be approximately one to one, while with air it will be about a thousand to one. Thus about a thousand times higher linear speed of flow is required for air. This is feasible as the viscosity of air, and thereby the pressure drop, is also about a thousand times less than that of water. The speed with which a temperature front moves in the core, is somewhat less than ten mm/hour.

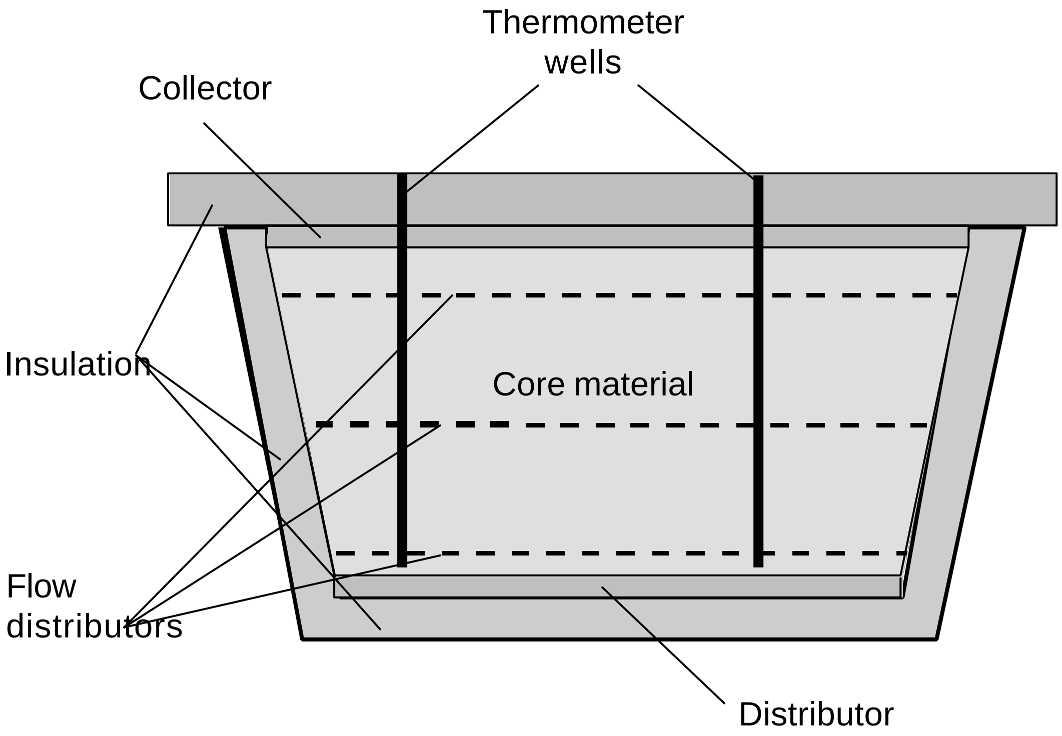

Figure 2.1b. *Construction of geophysically stable thermal core*

Chromatographic theory describes the spread of a thermal transition zone in terms of "theoretical steps". The height of a theoretical step is typically about the size of a pebble, and the full transition zone requires some 10-20 theoretical steps. For pebbles of about 20 mm diameter this gives a depth of some 0.25-0.4 m. For a 3 m deep core this means that the transition zone would take up about a tenth of the full core. With an overall movement of the zone of about 0.01 m/hour, there should be ample time for reaching thermal equilibrium. Compared to the use of chromatographic flow theory in chemical analysis (where this technology originates), there is a scale-up of particle size of about one to thirty. The stability of transition zones further depends on even flow across the cross section of the core. This will depend on accuracy of grading and placing of pebbles, and requires practical testing with actual materials. As shown in Figure 2.1b, flow distributors in the form of perforated plastic sheets may be used to obtain even flows across cores.

Another way of achieving stable transition zones is by means of tubing, placed in parallel horizontal layers. This appears to require a liquid (rather than air) as transfer medium. This type of construction might have tubing of about 10 mm diameter, and about 0.1m separation between tubes. Flow would be parallel in each horizontal layer, and serial from layer to layer. With a tubing density of about 100 m/m^3 of core, speed of flow within each tube would be about 0.07 m/hour, which should be sufficiently low to avoid problems with flow resistance. Cost of tubing is estimated at NOK 200-300/m^3 of core. An advantage with this type of construction is that heavy building waste, in particular, is fully separated from the circulating medium, and the crushed waste may be used as it is, hardly needing any grading.

2.2 INTEGRATION OF CORES WITH HEAT PUMPS INTO BUILDINGS

In this section we describe one way of integrating liquid-based enviro-cores into buildings. A principal layout is illustrated in Figure 2.2.

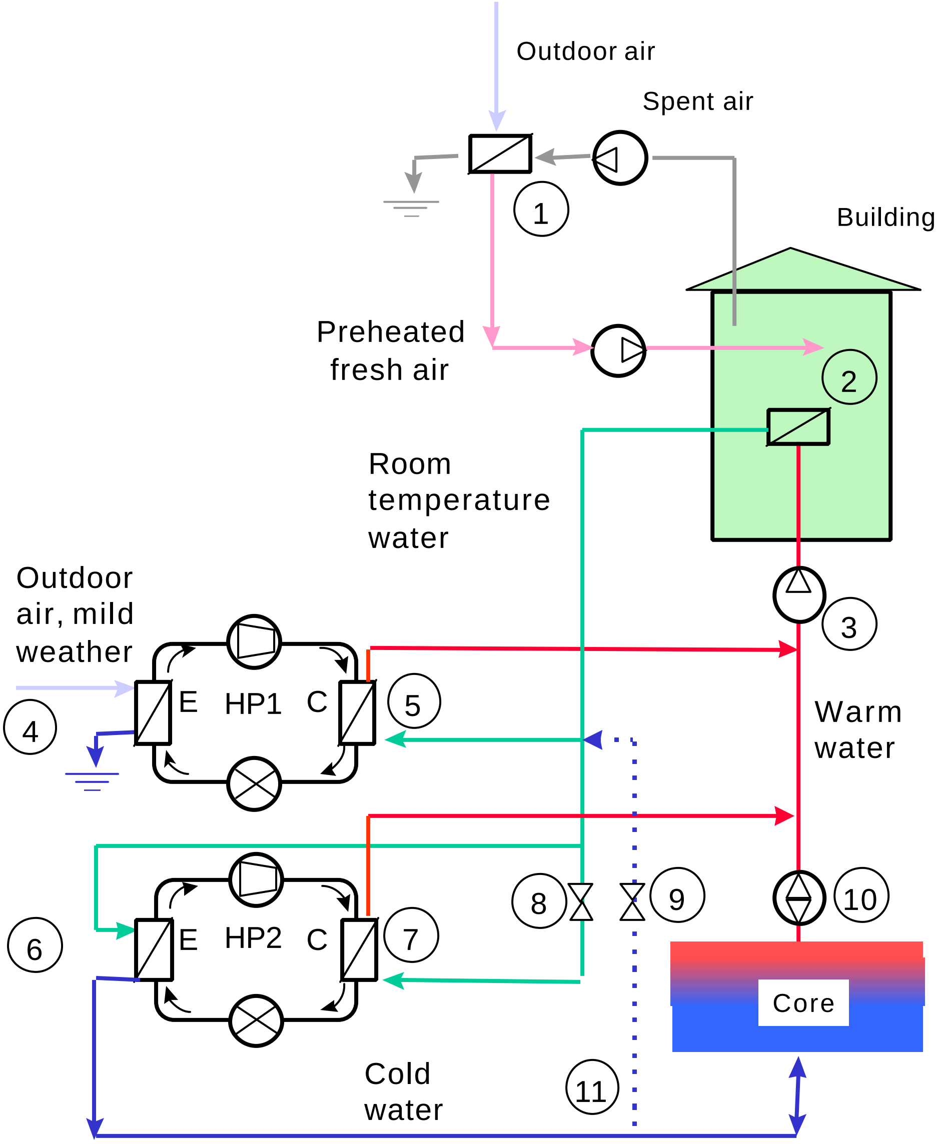

Figure 2.2: ***Principal piping diagram of water-based enviro-core***

Figure 2.2 appears to indicate a double set of heat pumps. This is for pedagogical purposes - in practice it is but one set of physical equipment performing two different roles. Further details are given below.

The use of water as heat transfer medium is advantageous in two respects in particular: liquid/liquid heat exchangers to the heat pump are compact and efficient, and distribution of heat (and cold) by means of ordinary, standard tubing is cheaper and simpler than air ducts. To obtain a high capacity in the core, the temperature difference between the warm and the cold zone in the core should be as large as possible. This implies that temperature in the cold part of the core should be as low as possible. It was thought originally that this could be set independently, with cooling from input of fresh air to the building. However, the lower temperature is actually determined by the low temperature side of delivering heat into the building, unless something special is done. In the system illustrated in Figure 2.2, a low temperature in the cold part of the core is achieved through a particular use of the heat pump. With liquid water in the core the low temperature is then adjusted to just above freezing.

This point is important. In the attached report by G. Eggen (2003) it is shown that a core to deliver 10 kW for 10 days (2400 kWh) requires a core volume of some 300 m^3, with a temperature drop in the heat transfer system in the building of 10º. Such a core would be too expensive to be practical. In the work reported here we have specified half this capacity (1200 kWh) for a detached home in the Oslo area, built according to insulating standards over the last 20 years. With heat delivered at 40 ºC to the building we then obtain a temperature difference in the core of some 35º, and a required core volume of 40-45 m^3. This is typically a construction 3 by 5 m in cross section and 3 m deep, which should be within reach for a lasting source of heating and cooling of such a home. Row housing, flats and office buildings have smaller surface to volume ratios, and require about half the energy or less for maintaining suitable indoor temperature.

The flow diagram as shown in Figure 2.2 reflects the situation when the enviro-core is used for heating. The system works for cooling of buildings as well, but then needs additional piping and valves. We describe the operation of obtaining heat from the core (hereafter called *heating*) and of charging the core (called *charging*). As described in section 1.6, enviro-cores obtain energy in several principally different ways: by charging in mild/warm weather and by making it possible to save surplus heat etc., in all cases to make the energy available as needed. The operation as shown in Figure 1 has the feature of matching the requirements of CO_2-based heat pumps well, particularly when return water from the building is close to room temperature.

We describe the functioning of the integrated system in Figure 2.2 in the two modes of heating and charging.

Heating

Heat is delivered into the building via feed pump (3) to a heat transfer system (2) which may be conventional radiators, floor heating, or heating connected to the ventilation system. Preferably solutions should be chosen that create a large temperature drop across (2). Figure 1 illustrates a separate, balanced ventilation system with recovery of heat from spent air. >From the transfer system water somewhat above room temperature (25 ºC) goes to heat pump 2 (HP2), where the flow is split to return some of it as warm water to feed pump (3), while the remainder goes as cold water to the cold side of the core. The purpose of the split stream is to increase the temperature difference in the core, and thereby its capacity. This mode of operation means that the core functions as an accumulator on both the warm and the cold side of the heat pump. (It is possible to operate the low temperature part of the core at the higher temperature of return water from the building (25 ºC) and thus to avoid heat pump 2, but the capacity of the core is reduced to about one third in this way). The ratio between the flows are adjusted to give a low temperature in the cold side of the core during winter, but may be adjusted to a higher temperature as required capacity is less for diurnal operation in spring and fall. In the core, cold water displaces warm water, which through feed pump (3) goes to heat the building. The cold front in the core moves upward at about 10 mm/hour.

Charging

Charging is done in mild weather according to weather forecasts, and/or when surplus heat is available as described in sections 1.5 and 1.6. Here we describe charging in mild weather (surplus heat is most readily obtained from spent air via heat exchanger (4), (not shown)).

Heat is obtained from ambient air by HP1 at (4), and delivered as warm water at about 35-40 ºC at (5). Depending on the requirement for heating of the building, a part may go via pump (3) to return as room temperature water (about 25 ºC) to (5), whence it is reheated. The remainder goes via the charging/extracting pump (10) to the thermal storage core. Here, it moves the transition zone downwards, and causes cold water to leave via bypass (11) and valve (9) to condenser (5) for re-heating. Heat pump HP2 is inactive during charging (i.e. this mode is not used in this case).

PART III: TECHNOLOGY AND MARKET

The concept of enviro-cores is closely tied in with the quest for sustainability. The well known work by Meadows et al (1972, 1992) demonstrates that continued growth at a fixed percentage each year, combined with attempts to handle environmental problems by cleanup operations, will surely lead to breakdown in economic life as we know it today. The only description that covers such a development is quite simply that it would be disastrous.

3.1 MARKET ASPECTS

The concepts described in this report involve very large amounts of energy (in the order of 20-25 TWh in Norway alone, for heating) if brought into widespread use. There is little doubt about the economic (and commercial) value of this per se. The main question is what it will require by way of resources, and thereby costs, to put into practice. Also, to get started, up front financing will be required. Three principal views may be had with respect to costs and availability of capital:

- *Marginal return on capital with respect to alternative investments now*
- *The value now of a large amount of energy available at very little cost in the future*
- *The value now of a sustainable future for coming generations*

The first kind of view is the situation confronting a commercial builder when raising a new building that is to be rented or sold, and where tenants will pay their energy costs. A typical discount rate in this situation is 15%, and the builder will weigh the costs for heating and ventilation against, say, the costs of a more expensive facade or more expensive siting.

The second kind of view is pertinent to a situation where the owner will pay the energy costs for a considerable time in the future, and where these costs cannot be avoided. A discount rate of 7% is commonly used for calculation of present value.

The last view considers the situation of seeking to prevent future emergencies (similar to e.g. defence-related expenses), and would seem to depend strongly on the awareness of the urgency of such emergencies. Ordinary economic calculations do not really apply.

The main circumstances making this last view at all relevant, are two. The first is the growing awareness of global consequences from human behaviour, and that has led e.g. to Norway signing the Kyoto protocol for control of fossil-fuel related carbon dioxide as a source of global warming. This also influences heavily the discussion of whether or not to rely on natural gas. The second circumstance is the situation of exponential growth (or even worse) seen all the way from the start of the industrial revolution, combined with the fact that introduction of remedial technology (such as the enviro-core discussed here) require many decades. In fact, the modelling by Meadows et al (1992) indicates that the problem simply cannot be solved by attaching cleanup activities to overcome environmental deterioration. The market situation of new concepts like enviro-cores depends heavily on how quickly the concerns for sustainability spread into the current economic practices for evaluation of present value.

There is, however, also another side. This is related to the problem of too hermetically sealed homes, in particular. The close relationship between enviro-cores and ventilation opens for solutions that combines good ventilation with minimal loss of heat. This adds a health aspect to the task of just keeping warm.

In his thesis dissertation, Gether (2002:300) discusses the problem of getting improved technological concepts off the ground. The normal situation is that the new technology will be highly competitive once available, but in order to get started, several firms need to work together. Unless all participants join in, there is little prospect for anything to happen. Such "catch-22" or "chicken-and-egg"-situations require particular measures to get around. Basically there are three ways ahead:

- *Vertical integration*
- *Formal networks*
- *Benchmarking*

Vertical integration means that some large firm commanding all required competence, equipment and capital, takes up the task and takes responsibility for bringing new technology into practical reality. This will happen primarily when a solid, lasting potential for income is manifest. Formal networks means that each firm carries on as usual, but agrees to play a role in a mutual effort to bring the new activity into being. This also require a a fairly clear view of lasting potential for income. The last approach implies an effort to demonstrate feasibility, with two main effects: The burden of proof is shifted, for those resisting change, from arguing that it cannot be done, to arguing why it should not be done here and now. Secondly, practical experience is gained that greatly reduces risks and uncertainty in estimation of time and costs.

There may be a situation of competition with other technological solutions towards the same ends, such as the use of bore-hole technology for seasonal storage. Eggen (2003) estimates costs by this technology at about NOK 2.- /kWh. This situation has not yet been evaluated in sufficient detail. Also, there may seem to be competition with approaches such as heat pumps in their own and solar energy, and also wind mills and photo-voltaic generation of power. However, the quest for sustainability appear to be such that all sources of sustainable energy supply will be required in parallel.

An interesting situation arises if overall environmental gains from enviro-core technology exceeds the environmental costs of generating electricity from fossil fuels, including natural gas. This would mean that it would be better to generate electricity for this purpose than to use the fuels directly for heating. There is a large scope for opportunities for improvement, and a steep learning curve is expected (cf. OECD/ IEA, 2001). With mass production, enviro-core installations should be within reach for most home owners and operators of larger buildings, and should also present an interesting option for new buildings.

As with all new development, the business opportunities opened for affiliated endeavour and enterprise should be kept in mind. Prosperity is closely related to technological improvement.

3.2 TECHNOLOGICAL ASPECTS

Apart from one aspect of the algorithm for optimisation discussed in section 1.5 and the practical construction and operation of thermal cores, all equipment is either standard components or well studied concepts such as CO_2-based heat pumps. Further work is required to obtain experience with construction and operation of thermal cores, to identify major cost drivers, and to demonstrate feasibility. Modelling of gain of energy under varying climatic conditions for both heating and cooling, and for different kinds of buildings needs to done, and is practical e.g. by means of the FRES modelling tools at NTNU/Sintef (cf. Mathisen et al 2003). Also, detailed schematics need to be worked out as basis for the optimisation algorithm. All of this is, however, standard components and existing competence.

References

Dincer, I. and M. A. Rosen (2002): *Thermal Energy Storage. Systems and Applications*. John Wiley & Sons, Ltd, Chichester, UK

Eggen, G. (2003): *Feasibility study. ENVIRO-CORES: Thermal Storage Integrated with Heat pumps.* InterConsult, Trondheim

Gether, H., (2002): *Strategy as a Contribution to Prosperity and Sustainability. Overall Optimisation of Technological Value Sequences*, Dr. Techn. Thesis, Faculty of Engineering Science and Technology, NTNU

Mathisen, H. M., J. Stang and K. Kolsaker (2003): *ENVIRO-CORES: A simple description of HVAC-systems and heat flows in buildings*

OECD/IEA (2001): *Introduction to Experience Curves for Energy Technology Policy,*

Oslo Kommune (1999): *OMMAT - Industriell tilnærming til ombruk av materialer. Bærekraftig utvikling og redusert avfall med fokus på tegl og murverk.* Oslo Kommune, Statsbygg, Gether AS