SIMULATION AND OPTIMIZATION OF AN INTEGRATED ENERGY SYSTEM

K. Hostrup, N. Houbak

Department of Energy Engineering, Technical University of Denmark

ABSTRACT

Cogeneration of electric power and heat is a traditional way to utilise 'waste' heat. In this paper an energy system coupling the production of power, fresh water and ice blocks in trigeneration is analysed. One of the advantages of this system is the coupling of 3 different outputs where 2 of the outputs (water and ice blocks) can easily be stored. All the components of the system are well known but the coupling of the components makes the system complex. The system has been modelled and simulated dynamically and an optimisation of the system has been performed. A special feature of this system is that the saline water is used both for desalination and for freezing ice blocks.

KEYWORDS

Trigeneration, energy system, desalination, ice block plant, saline water

1 INTRODUCTION

At remote locations further development could require access to electrical power, fresh water and cooling capacity as an example take an island with a small fishing industry.

An energy supply for an island, where fishing is the main part of the outcome, is described. On the island there is a general need for power but also a need for ice blocks for the fishing boats and for drinking water. The drinking water could be produced by desalination of seawater. In this project the use of waste heat for desalination has been considered. With these needs to be fulfilled a combined energy system would be a good solution as the water could be produced from waste heat and both the ice-blocks and the water can be stored.

2 SYSTEM DESIGN

A system is designed that is able to fulfil the needs described above. The system consists of a diesel engine with a generator, an ice block plant with storage, a desalination plant and some auxiliary equipment such as a heat pump, heat exchangers and pumps. A model of the plant is showed in Figure 1. From the figure it can be observed that the only energy input to the system is the fuel for the diesel engine. The engine delivers electric power to the local power grid, the ice-block plant and the heat pump. The waste heat (exhaust and jacket cooling) from the engine will be used in the desalination plant. The remaining part of the heat for desalination is provided by the heat pump, which converts waste heat from the desalination plant itself and the ice block plant. Seawater is used in the process of desalination for freezing and for cooling in the condenser in the ice block plant.

2.1 Mathematical modelling

The modelling is mainly based on conservation of mass and energy. The turbo charged diesel engine is modelled by a constant fuel/air ratio and an efficiency depending on the load. The heat pump and the ice block plant have been modelled by a temperature dependent COP-value. The desalination plant is a multi-effect plant and consists of 2 flashes and a cooling step as described in [2]. In the first flash, preheated seawater is evaporated at a pressure corresponding to a boiling temperature of 70°C. The heat necessary for the evaporation comes from the heat pump and the cooling water from the engine. In the second flash the pressure is lowered and it correspond to a boiling temperature of 45°C. The condensation of the vapour from the first flash provides heat for the second flash. After the last step, the vapour from the second flash is condensed using seawater. The pressure of the last evaporation flash depends on the temperature of the cooling water. The 3 steps are basically modelled as heat exchangers with evaporation and condensation. The heat exchangers are modelled by a constant value of U·A and a maximum efficiency. The pumps are modelled with a constant efficiency and the work they have to deliver depends of the length of the pipes and the pressure loss in the heat exchangers. It also appears from Figure 1 that each component has connections to most of the other components. A set of coupled differential and algebraic equations is set up using the above assumptions to be able to simulate the behaviour of the system during 1 day.

2.2 *Solving the equations*

To investigate the detailed operation of the plant it is necessary to solve the equations dynamically but much useful information about the system could be found with a static solution. This is obtained using EES (Engineering Equation Solver). For the dynamic solution a dynamic solver written in Fortran was used. The equations will form a coupled system of both differential and algebraic equations (a so-called DAE system). The 'lsodi' solver from Lawrence Livermore, see

N. Houbak, niels.houbak@mek.dtu.dk

http://sunsite.doc.ic.ac.uk/computing/general/netlib/odepack/index.html, has been used with necessary care on initial guesses, solution method etc. The lsodi solver uses a BDF (backward differentiation formula) method [1] In this case the solver was forced only to use a first order BDF-method (a backward Euler method) because higher order could cause trouble with both differential and algebraic equations.

3 SALINE WATER

The saline water is used both for making ice blocks and it is desalinated to get drinking water. The saline water is thermodynamically handled as a to-component solution. The big advantage in freezing saline water instead of pure water is the saving of the energy for desalination before freezing. The ice blocks need not be of drinking water quality since it is, used for keeping fish cold. The freezing point for saline water is lower than for normal water and it decreases for increasing salinity. The saline water freezes by freezing out pure water, this increases the salinity and thus further decreases the freezing point in the remaining solution. In this way the freezing becomes a continuous process when the temperature is lowered in the iceboxes. This makes it possible to model the freezing by a temperature dependent heat capacity. Such a graph has been made in [3] from enthalpy measurements of the melting of the ice. In [3] there are only a limited number of measurements in the zone where most of the melting appears. From the enthalpy measurements it is possible to construct a graph with the heat capacity (cp.) as a function of the temperature including the energy required for cooling. The integration of the heat capacity-curve shows that not all off the rise in enthalpy from the measurements has been included. Therefore a new analysis of the measurements has been done, and the new graph of heat capacity as a function of temperature can be seen in Figure 2. If the temperature is lowered below –21°C the saline water solution will form some eutectic, but this is not treated further in this paper.
The freezing of the saline water requires a lower temperature than freezing of pure water in order to get a reasonable amount of ice. The amount of unfrozen water can be found by the salinity of saline water with a freezing point at the given temperature and then using mass balances. An analysis using this model shows that the solution at no point is near saturation. The energy used for cooling the concentrated saline water that is left over is off course lost.

4 Plant Conditions

The design of the plant is based on information of the needs of a 'typical' island as described before and the plant conditions are assumed to be the standard in hot areas: sea water 32°C and a salinity of 34.5g/kg and the temperature of the air is 35°C. A parameter variation around these values has been performed. The high temperatures require more energy both for cooling and for desalination (the temperature of the cooling water is high).

5 SIMULATON OF THE OPERATION OF THE PLANT

The operation of the plant aims at fulfilling a given need of power, drinking water and ice blocks. The power demand is given for each hour and linear interpolation is used for intermediate values. The demand for ice blocks and water has to be fulfilled on a daily basis. Different ways of coupling the components together and ways to control the system are considered. The goal is a high gain in synergetic effect. An overall control strategy for the system i.e. with respect to how much power the engine should deliver, and how much power every component should get, is considered. 2 different control strategies are investigated. One way is first to fulfil the demand for power supply and then share the rest of the power between the ice-block plant and the heat pump. If the ice-block plant doesn't need that much energy the engine will be turned down. The other way is to deliver power for the supply and then deliver to the heat pump depending on how much power is needed and how the engine is running. The remaining power will then be used for pumps and for the ice-block plant. For such a strategy the allocation of power for the three consumers: Power supply, heat pump and ice block plant, can be seen in Figure 3.

6 RESULTS

The system is mainly evaluated on the basis of energy savings compared to a system consisting of separate productions. Also the way of control and the changes in the external conditions has been considered.
The profit of the whole plant will be highest if the drinking water could be produced without using the heat pump and solely by waste heat from the engine. This can't be obtained in this situation, and in general the possibilities would be small. By adding the heat pump, the system gets much more flexible, and it is still better than using an electric heat source directly for the desalination.
The first evaluation is an overall comparison of other ways of gaining the same products; water, ice blocks and electricity with the system described above. In Table I, 4 test cases are compared on the basis of the energy consumption in 1 day for fulfilling the needs above . The first one (column) is the system described in this article, the following two are for the energy consumption of the components if they where not connected to each other. Number two with an overall efficiency from heat to electrical power of 40% and number three with an overall efficiency from heat to electric power of 38%. In the last case the energy consumption is estimated if the ice had to be made from fresh (and therefore desalinated) water. The energy requirement for the desalination is taken from [2] to be 1.5 MJ/kg of fresh water.
It is seen that using an integrated system could save more than 30% of the input of energy. If the system is compared with one where the ice blocks where frozen from desalinated water more than 50 % of could be saved. This is a new technique and requires some research in the freezing mechanism.

An evaluation on how to control the system has also been done. The evaluation was done on either operating the engine with constant fuel input all the day, or operating the engine at maximum load until the ice is frozen and then turning the engine down.
It has been found that the best way to run the system is a constant power input during a day. This gives the ability of operating the engine with a best overall efficiency and most of the waste heat can be used. It also indicates, that an optimal operating of the system would require the knowledge of the demand in advance. In Figure 4 the total energy used is shown as a function of the amount of water and ice produced.
When operating the system with an almost constant power input. To different ways to do this has been investigated. The simplest way is to have a constant ratio between the electricity used for the heat pump and that used for the ice block plant. The other way has been to pre-program how much power the heat pump should get dependent on the demand of electricity. The remaining electric power is then allocated to the ice block plant as described in chapter 5.
The two different strategies have been compared. As can be seen in Figure 5 there is no big difference between the two strategies. In the end it could turn out that one strategy might be less complicated to implement than the other (or that a third kind of control is simpler and better)

The effect of changes in the temperature and salinity has been investigated in the production of drinking water. A location of the plant has been chosen with standard se water (see chapter 4) for seawater. It turns out that with increasing temperatures and salinity of the seawater, the plant requires more energy for the same output. For the increase in temperature it could be explained by the need of more cooling water both for the ice block plant and also for the last step in the desalination plant. If the temperature of the seawater varies too much, the whole design of the plant needs to be re-evaluated. The consequence and energy required pr kg of drinking water due to a variation in the salinity be shown in Figure 6. An increasing salinity is responsible for a higher boiling temperature. Lower heating capacity of the cooling water is responsible for the increase in energy used for a higher salinity.

7 CONCLUSION

The coupling of the energy system is showed to be able to work properly. As expected there is a large energy saving by coupling the system. If the system is compared to a system where power, ice blocks and water are produced separately more than 30% of the energy could be saved. The properties of saline water has been studied for the possibilities of freezing and it has been shown that more than 50% of the energy could be saved by a combination of freezing saline water and using the components as an energy system. When either the temperature or the salinity is increased the demand for energy is also increased.
The 2 different ways of controlling the system has been analysed and no big differece between them has been found, as long as the conditions make the system operate with only small variations in the fuel input.
Another way of operation that hasn’t been investigated is the ability of storing products easily. Both water and ice could be stored with low cost over a longer period. In this way they could also serve as storage for electricity, as the electricity production can be increased in periods with lower or no ice and water production.

8 REFERENCES

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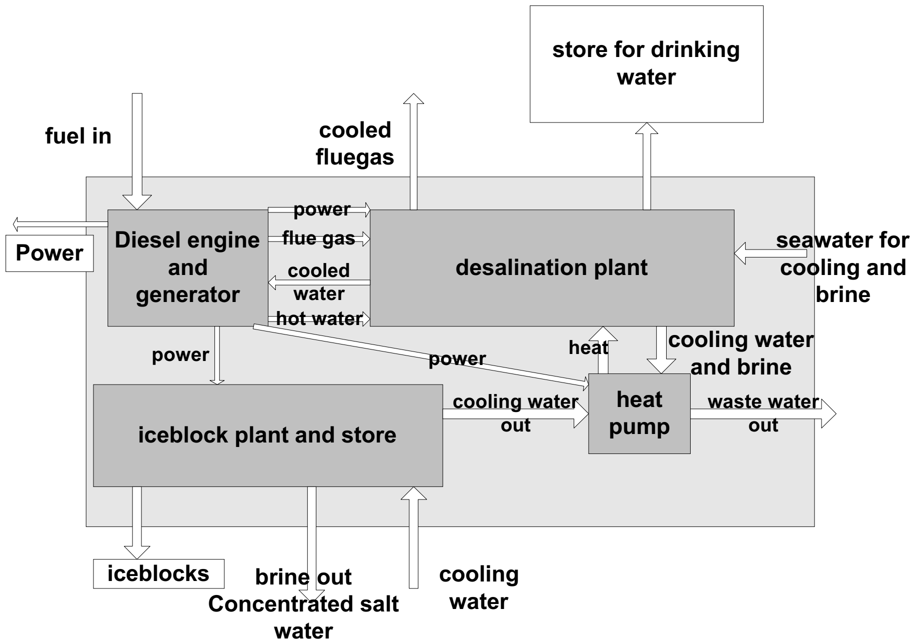

Figure 1 Principle drawing of the plant

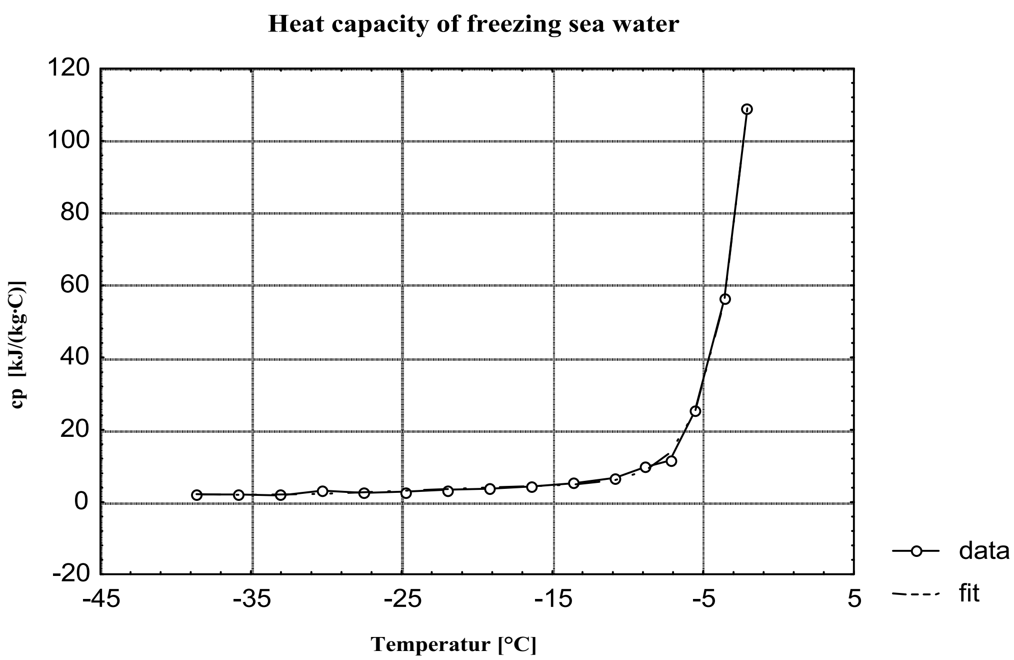

Figure 2 Heat capacity of freezing seawater

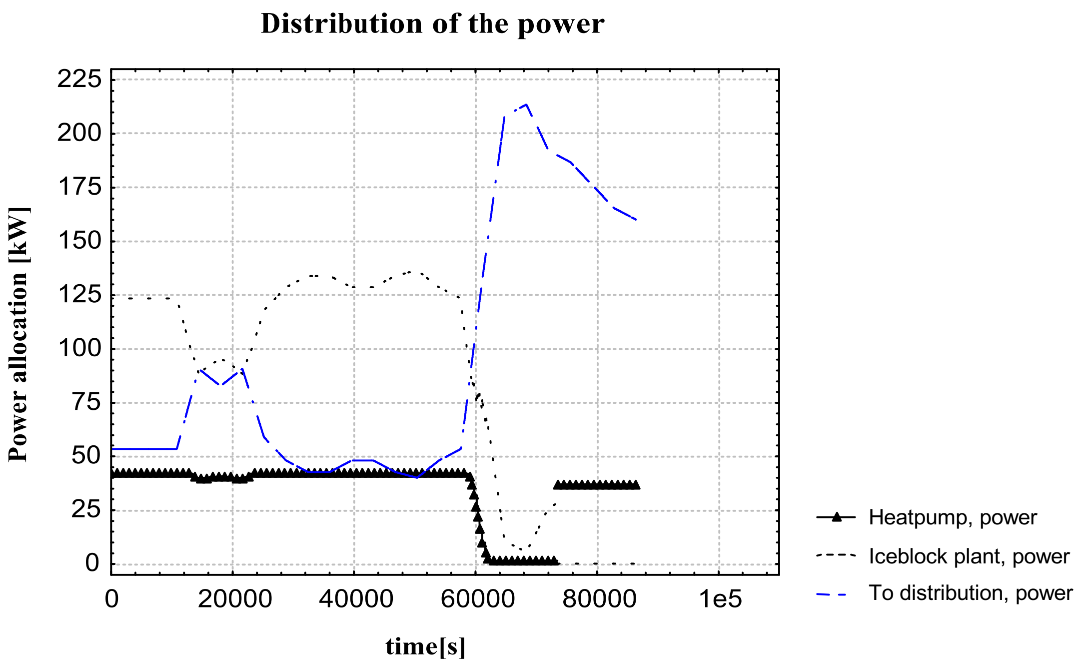

Figure 3 Allocation of the power for the three different consumers during 1 day

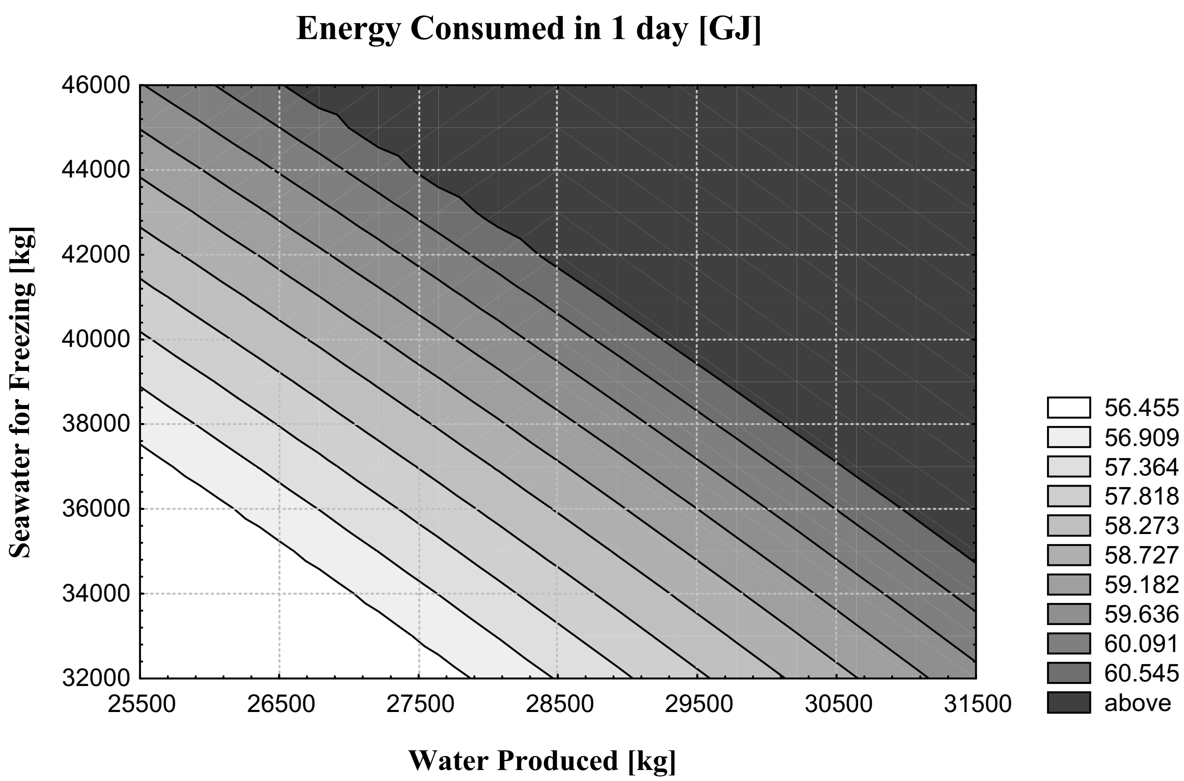

Figure 4 Daily energy consumption for different amounts of Water and ice blocks in GJ

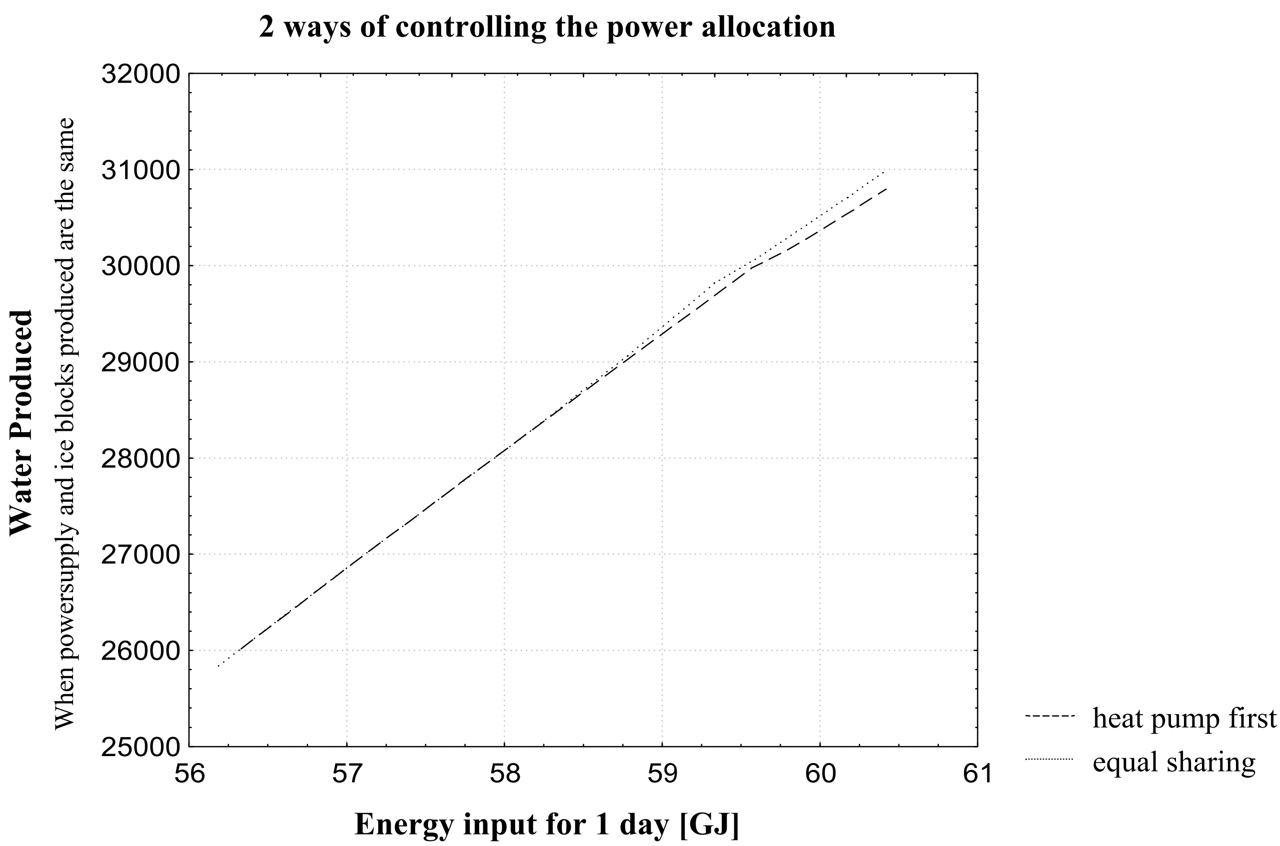

Figure 5 controlling strategies

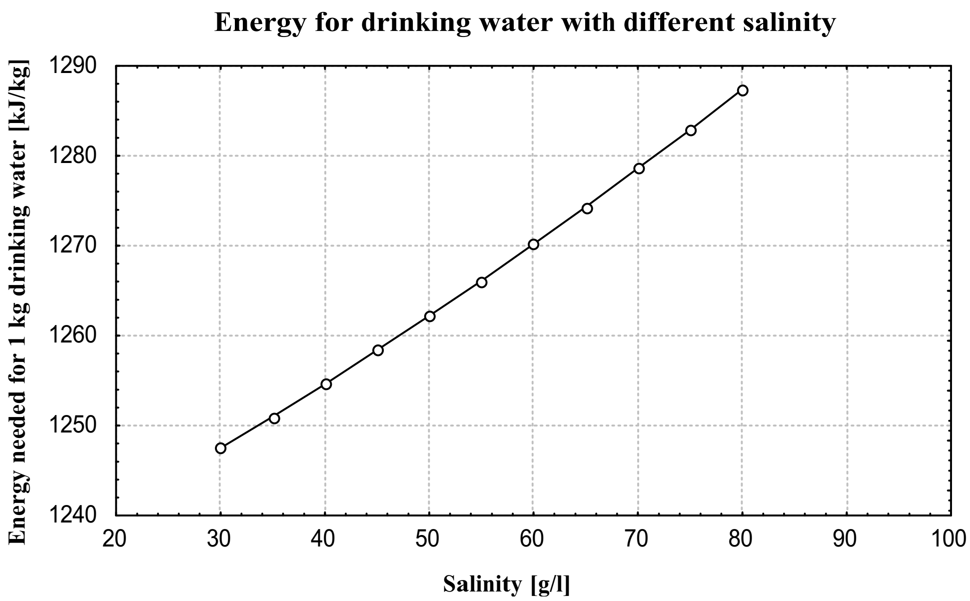

Figure 6 The effect of changing the salinity of the water

Table 1 Comparison between the system and 3 different stand alone systems

Products	1 system	3 plants η_{power} = 0.4	3 plants η_{power} = 0.38	3 plants fresh water
ice	----	41.0 GJ	41.0 GJ	41.0 GJ
water	----	21.1 GJ	22.2 GJ	60.3 GJ
electricity	----	20.5 GJ	21.6 GJ	20.5 GJ
overall	56.7 GJ	82.6 GJ	84.8 GJ	121.8 GJ
saved	0 %	31%	33 %	53 %