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APPLICATION OF ALTERNATIVE TECHNOLOGIES IN COMBINATION WITH NUCLEAR ENERGY

Summary

Studies show that the developed world will need even more energy in the future. At the same time, the reserves of fossil fuels are rapidly running out. Due to ecological and demographic impacts, there is a high probability of a series of changes occurring on our planet over the next fifty to seventy years. One of the best ways how to avoid global warming effect is the use of hydrogen technologies. Hydrogen is used widely by petrochemical, agricultural, manufacturing, food processing, electronics, plastics, metallurgical, aerospace and other industries. The consumption of hydrogen is possibly in many ways but most perspective is the use of fuel cells. One of the biggest problems in hydrogen technology is to produce enough hydrogen for use in all technical applications. One of the most optimistic procedures is hybrid thermochemical decomposition of water and solar photochemical production of hydrogen. In the presented article, we have tried to develop energy analysis which model shows the best results regarding Slovenia region.

Key words: *hydrogen technology, thermodynamics, thermochemical cycle, district heating, heat pump technology*

1. Introduction

Transport and energy sector are the major ecological pollutants. One of the most important factors in improving the ecology will therefore undoubtedly be the introduction of environmentally friendly technologies, which certainly include hydrogen technology, methanol technology. Japan, being one of the most advanced countries, has already started the process of introducing the fuel cells in the railway sector, for slower trains and the company Toyota started in 2015 with serious production of hydrogen cars called Toyota Mirai. Also Germany started with production of submarines and ships with fuel cell technology…

Rather than deriving hydrogen from fossil fuels, a promising alternative is the thermochemical decomposition of water or production of hydrogen from solar energy in connection with nuclear power plant.

From a nuclear power plant we can also achieve a lot of heat, so called waste heat. This heat can be used for instance in a district heating systems. Less than 1 % of the heat produced in nuclear reactors in the world, is used for district heating. Examples of a good practice in this field are nuclear power plants Bilibino (Russia), Beznau (Switzerland) and Bohunice (Slovakia). There was also a project for a district heating system for Helsinki (Finland) [1]. All the studies and research in terms of nuclear power plants in combination with district heating systems are published regularly in TECDOCs by International Atomic Energy Agency IAEA.

2. The hydrogen production in combination with nuclear power plant

Nuclear power plants are intended to generate electricity. There are different types of nuclear power plants in the world, differing mainly by the type of reactors. The most common type is the pressurised water reactor (PWR), fitted to more than half of the nuclear power plants. It is assumed that a PWR nuclear power plant is built in the Dolenjska or Zasavje region. The PWR nuclear power plant comprises a primary, secondary and tertiary circuit. PWR nuclear power plants almost always operate at the project point, i.e. at the point of the highest efficiency. In addition to high-quality electrical energy, the nuclear power plant also produces steam of very high quality. High-quality steam is a prerequisite to running a number of technologies, in particular biofuel production, district heating…. In the event of constant power generation from a nuclear power plant any excess electricity has to be consumed in a useful way. Therefore, a nuclear power plant may, in principle, be combined with the technologies as follows:

- Sale of electricity as an export product;
- A combination of a nuclear power plant with a reversible pump turbine. This combination is the most frequent in the world;
- A combination of a PWR nuclear power plant with a district heating system to provide heating to a nearby city;
- A combination of a PWR nuclear power plant with the production of bio fuels, primarily bioethanol, biomethanol and biodiesel;
- A combination of a PWR nuclear power plant with hydrogen production.

Some basic information concerning the general PWR [2-6] type of typical nuclear reactor are presented in Fig. 1 and Table 1.

Table 1 Important data for PWR secondary system

Steam pressure before high pressure turbine [5]	6.3 MPa
Steam temperature before high pressure turbine [5]	299 °C
Mass flow in secondary system [5]	5078 t/h
Steam pressure in low pressure turbine [7]	1 MPa
Condenser pressure [7]	6.6 kPa
Condenser temperature [7]	37.8 °C

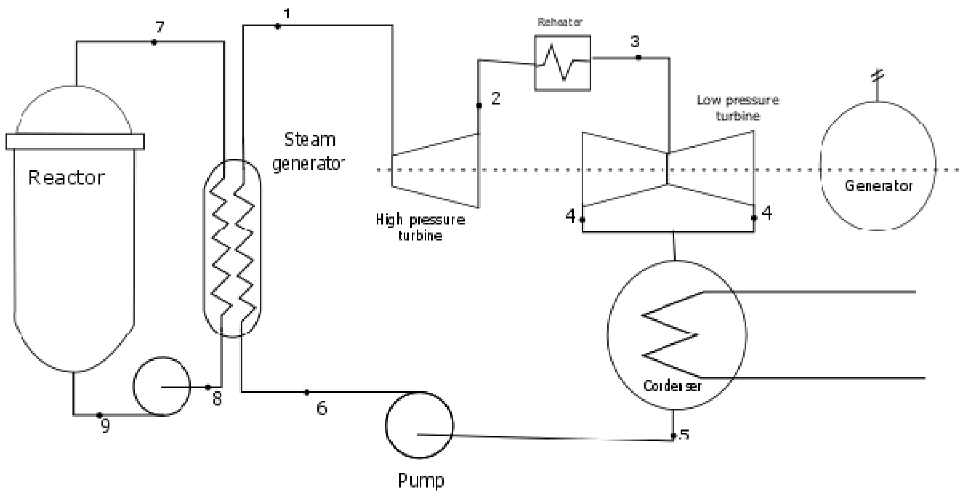

Fig. 1 PWR secondary system

In principle, it is possible to produce hydrogen in two ways: from fossil fuels and from water. Processes producing hydrogen from fossil fuels are very cost-effective, however, a construction of such a facility in the environment would be an issue from several points of view: enormous emissions of CO2, factories pollute the environment with other waste as well. This is why the next part of this article focuses mainly on obtaining hydrogen from water. Nuclear power plant produces high quality electricity, heat and vapour. Regarding hydrogen production is possibly in connection with nuclear power plant produce hydrogen in next ways:

- Electrolysis [2, 8-11] is a proven, commercial technology that separates water into hydrogen and oxygen using electricity. Net electrolysis efficiencies (including both electricity and hydrogen generation) are typically about 32%.

Rather than deriving hydrogen from fossil fuels, a promising alternative is thermochemical decomposition of water [2-5, 11]. Thermochemical cycles to produce hydrogen promise heat-to-hydrogen efficiencies up to about 50%. In scientific literature, there are more than 200 thermochemical cycles [5-9], majority of which was never tested as pilot projects. Most of them are being developed in the USA, Japan, Canada, France. Especially interesting are the thermochemical hybrid cycles, which, apart from waste heat, require electrical energy from nuclear power plant to operate. However, most currently existing thermochemical hydrogen production cycles require a temperature of higher than 500^{o}C [8, 12-13], which cannot be satisfied by current large scale nuclear reactors, although potentially can be satisfied by future generation nuclear reactors (i.e., Gen-IV reactors) [14]. This article examines the economic analysis of a specific cycle called the copper-chlorine (Cu-Cl) cycle, with particular relevance to nuclear-produced hydrogen. A conceptual schematic of the Cu-Cl cycle is shown in literature [2-3, 11]. In the Cu-Cl cycle, water is decomposed into hydrogen and oxygen through intermediate Cu-Cl compounds. The CuCl cycle is constructed as closed loop consisted from five steps [12, 15]. The mentioned five steps could we classify as HCl production step, oxygen production step, copper production step, drying step and hydrogen production step. The maximum temperature in the process is 550 °C, with new development of CuCl cycle we wish to reduce the maximum temperature approximately to 300 °C. Nuclear-based "water splitting" requires an intermediate heat exchanger between the nuclear reactor and hydrogen plant, which transfers heat from the reactor coolant to the thermochemical cycle. An intermediate loop prevents exposure to radiation from the reactor coolant in the hydrogen plant, as well as corrosive fluids in the thermochemical cycle entering the nuclear plant. Fig. 2 shows energy requirements for CuCl process [16].

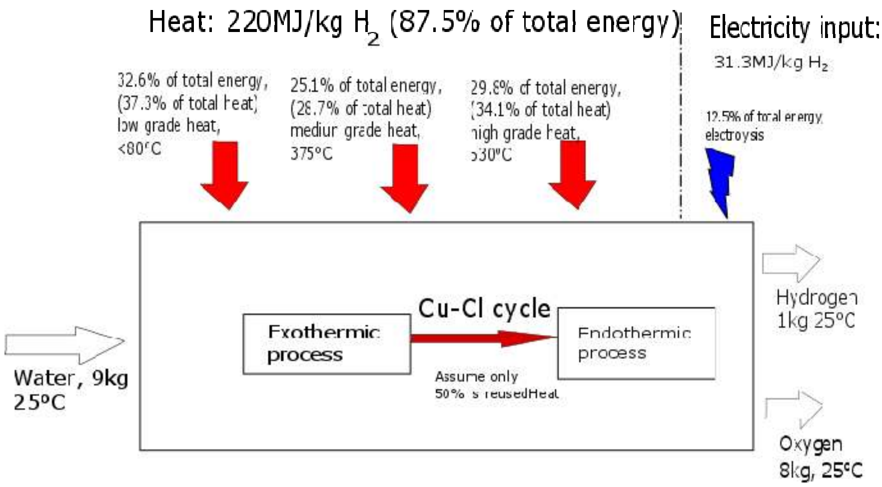

Fig. 2 CuCl process energy requirements for process [11]

- Photoelectrolysis and photochemical hydrogen production systems [12-14]. The detailed description of both systems is published in the literature [14]. Both systems are now under strong development, the overall production efficiency is 16% for electrolysis and 10% for photochemical hydrogen production systems.

The production price of hydrogen was calculated in relation to the PWR nuclear power plant. The results are indicated in Fig. 4, namely the price of hydrogen produced through electrolysis or using a CuCl process. The information used for the CuCl process was that 1 MWh of electricity costs between 35 to 80 euro. The assumption concerning the hydrogen production through electrolysis was that 79 kWh of power (51% efficiency) is required. The price of thermal energy from a nuclear power plant was calculated from the Rankine process with the assumption of steam consumption at the low-pressure stage of the turbine. For steam or heat extraction from a low-pressure stage the heat extraction before the low-pressure stage of the turbine was assumed. As it is evident from the figure and the table, hydrogen production by means of a thermochemical process is much more economical. Figure shows the installation of a heat exchanger for the extraction of the necessary thermal energy. Fig. 1 shows that the highest temperature in the secondary circuit of the PWR nuclear power plant is 300 °C. Therefore, it is necessary to ensure any excess energy through renewable sources or by using electricity in the sense of electric resistance or induction heating, thereby reducing the net power generation from a nuclear power plant. Fig. 3 shows the application of PWR nuclear power plant in combination with CuCl cycle. Fig. 4 shows calculated prices for hydrogen production without investment costs.

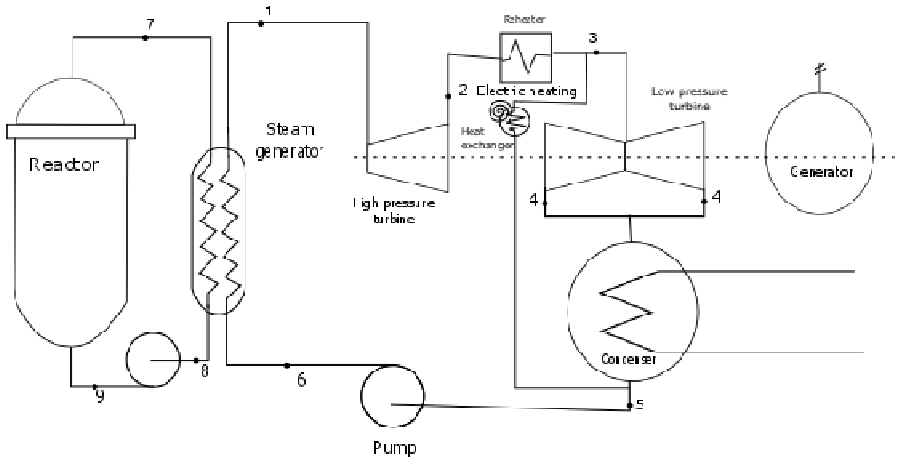

Fig. 3 Typical flow diagram for combination of PWR nuclear power plant with CuCl cycle

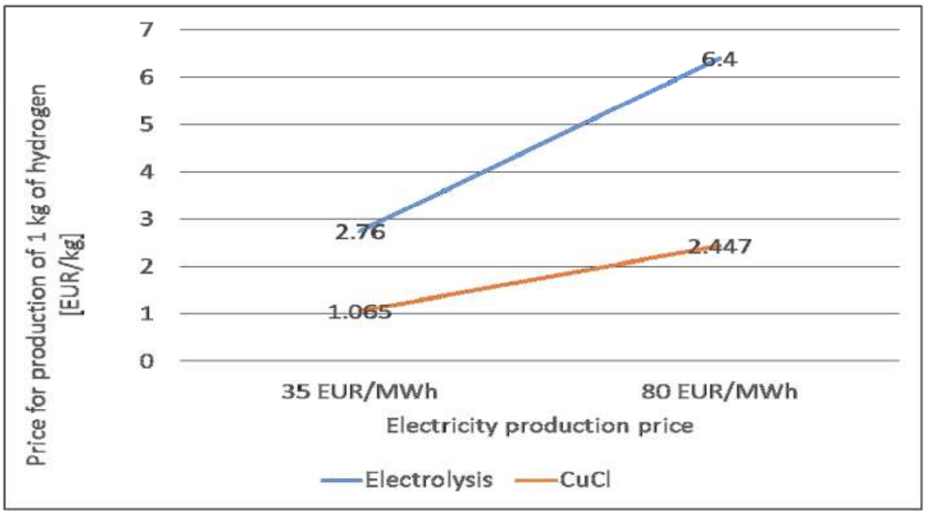

Fig. 4 Comparison of price for hydrogen production

3. District heating demand in Novo mesto municipality

District heating is one of the potential applications of a PWR nuclear power plant. In our case, we have explored the possibility of district heating of the nearby Novo mesto municipality. Novo mesto is an economically and culturally very developed municipality. The data on the demand for thermal energy for heating and thermal energy for the industrial application is indicated in Tables 2, 3 and 4.

Table 2 Main parameters of the Novo mesto municipality

		Thermal energy			Electrical energy
		City of Novo mesto	Other settlements	Total municipality	Total municipality
Population		23174	12479	35653	
Final energy consumption	GWh/year	496	105	601	295
Final energy consumption (excluding transport and industry)	GWh/year	199	102	301	95

Table 3 Main heating parameters of the Novo mesto municipality

	Final energy consumption for heating and technology		
	MWh/year		
	City of Novo mesto	Other settlements	Total municipality
Heating	225663	91064	316616
Sanitary water	30567	13692	44259
Technology	239674	0	239674
Total	**495794**	**104756**	**600550**

The thermal energy demand in Novo mesto was calculated according to the average annual consumption.

Table 4 Novo mesto maximal heating load

	Residental heating	Sanitary water	Thermal energy for industry	Total
MW	45.6	3.5	48.5	97.6

It is evident from the above table that approximately 100 MW of thermal energy has to be provided to meet the Novo mesto district heating demand [17].

4. The district heating of city Novo mesto with combination of nuclear power plant

4.1 The use of heat exchanger for district heating in secondary system

Regarding classical PWR nuclear power plant of Westinghouse type (Fig. 3), a heat exchanger would be installed behind the moisture separator and reheater and in front of the low-pressure turbine. Otherwise all inlet and outlet flow rates should be calculated again, because of the new design of the system. Steam extraction in front of the low-pressure turbine is also the most cost effective.

In order to meet the district heating requirements, 100 MW of heat is needed. A calculation will be made for the amount of low-pressure turbine power output reduction in the case of a 15 % heat loss. The results thus obtained will provide a basis to compare a heat and electricity prices at energy prices from € 35 per MWh to € 80 per MWh [18]. Fig. 5 shows the heat exchanger location [1].

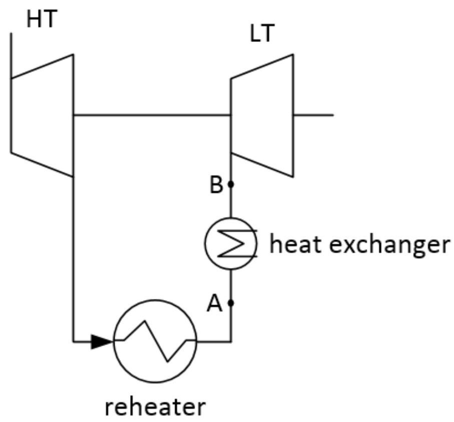

Fig. 5 Location of heat exchanger or steam extraction

The only parameter subject to change is enthalpy in point B (see Fig. 5). It is to be calculated using Equation (1).

$$\dot{Q} = \dot{m}_{LP} \cdot (h_A - h_B) \tag{1}$$

4.1.1 High-pressure turbine

The mass flow rate into the high-pressure turbine is $\dot{m} = 1410.56\,\text{kg/s}$. The expansion in the turbine is not isentropic but with the efficiency $\eta_{HP} = 0.8$. The unknown values are taken from the mechanical engineering handbook, whereas the remaining values are calculated. Finally, the turbine power output is obtained using Equation (2):

$$\dot{W}_t = \dot{m} \cdot (h_{iHP} - h_{oHP}) = 1410.56 \cdot (2751.5 - 2513.5) = 335.7\text{MW} \tag{2}$$

Then the vapor enters a moisture separator and reheater before the low-pressure turbine. The quality of vapor is $x_{LP} = 0.87$.

4.1.2 Low-pressure turbine

The calculation is similar as with the high-pressure turbine, yet with different data. Power output obtained in the calculation using Equation (3):

$$\dot{W}_t = x_{LP} \cdot \dot{m} \cdot (h_{iLP} - h_{oLP}) = 0.87 \cdot 1410.56 \cdot (2997.8 - 2340) = 807\text{MW} \tag{3}$$

Certain data from this section will be used in the next one to see how much the low-pressure turbine power output would be lower should the steam be used for district heating.

4.1.3 15 % loss

The required heat in the case is $\dot{Q}_{15} = 1.15 \cdot 100 = 115MW$, then by using Equation (1) we calculate h_B. This value is then set in Equation (4) and the low-pressure turbine new power output is computed using Equation (5) and by how much the low-pressure turbine power output is lowered using Equation (6):

$$h_{oLP} = h_B - \eta_{LP} \cdot \left(h_B - h_{f2}\right) \tag{4}$$

$$\dot{W}_{t15} = 0.87 \cdot 1410.56 \cdot \left(2916.3 - 2323.3\right) = 727.7\text{MW} \tag{5}$$

$$\Delta P_{15} = \dot{W}_t - \dot{W}_{t15} = 807 - 727.7 = 79.3\text{MW} \tag{6}$$

Now we will calculate for each case separately the minimum costs of 1 MWh of heat to compensate the cost of electricity, which is € 35 per MWh to € 80 per MWh [18]. Let us assume a 24 h operation. The values are indicated in Table 5 and shown in Fig. 6.

An example of the calculation for the heat price with the electricity price of € 35 per MWh is shown below (see Equations 7 to 9) [1].

$$\Delta P_{15} \cdot 24h = 79.3 \cdot 24 = 1903.2\text{MWh} \tag{7}$$

$$c_1 = 35 \cdot 1903.2 = 66612€ \tag{8}$$

$$d_1 = \frac{c_1}{115 \cdot 24} = \frac{66612}{2760} = 24.1 \frac{€}{\text{MWh}} \tag{9}$$

Table 5 Computed values

Electricity price (€/MWh)	Heat price (€/MWh)
35	24.1
40	27.6
45	31.0
50	34.5
55	37.9
60	41.4
65	44.8
70	48.3
75	51.7
80	55.2

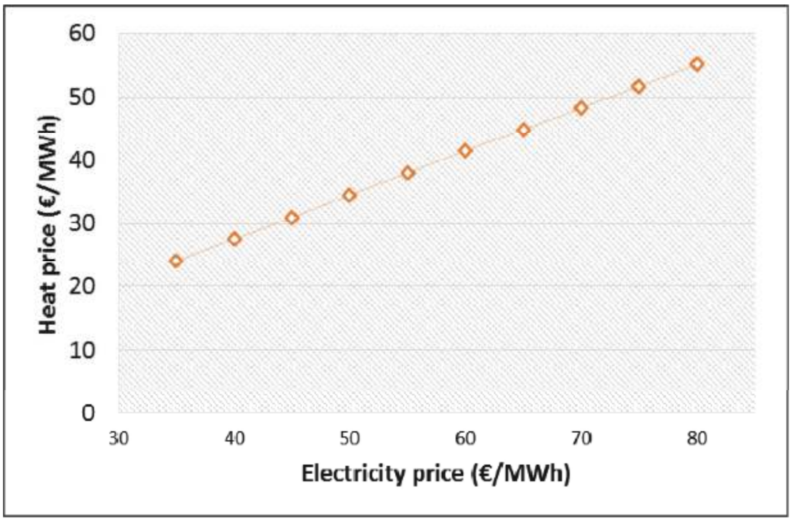

Fig. 6 Heat price movement depending on electricity price

4.2 The use of heat pumps for district heating in ternary system

In this case we use the waste heat from ternary system of nuclear power plant. In the heat pump as working fluid we have used the fluid R365mfc [3]. The presented working fluid has critical temperature at 180 °C (Figs. 7-8).

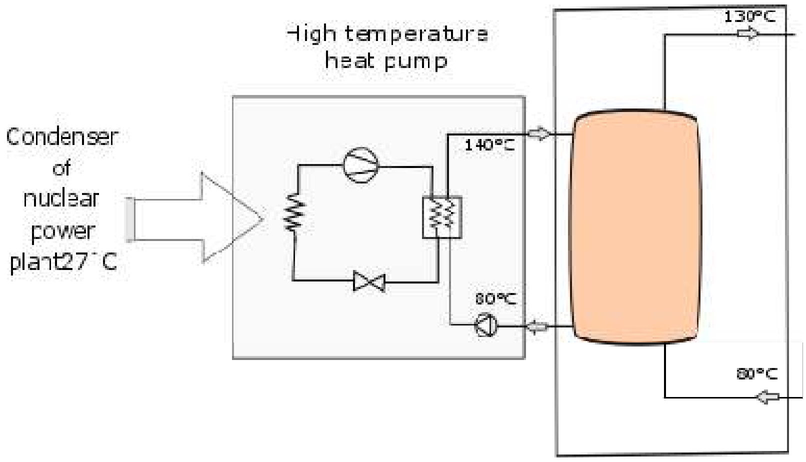

Fig. 7 Technical graph for heat pump application in PWR system for district heating

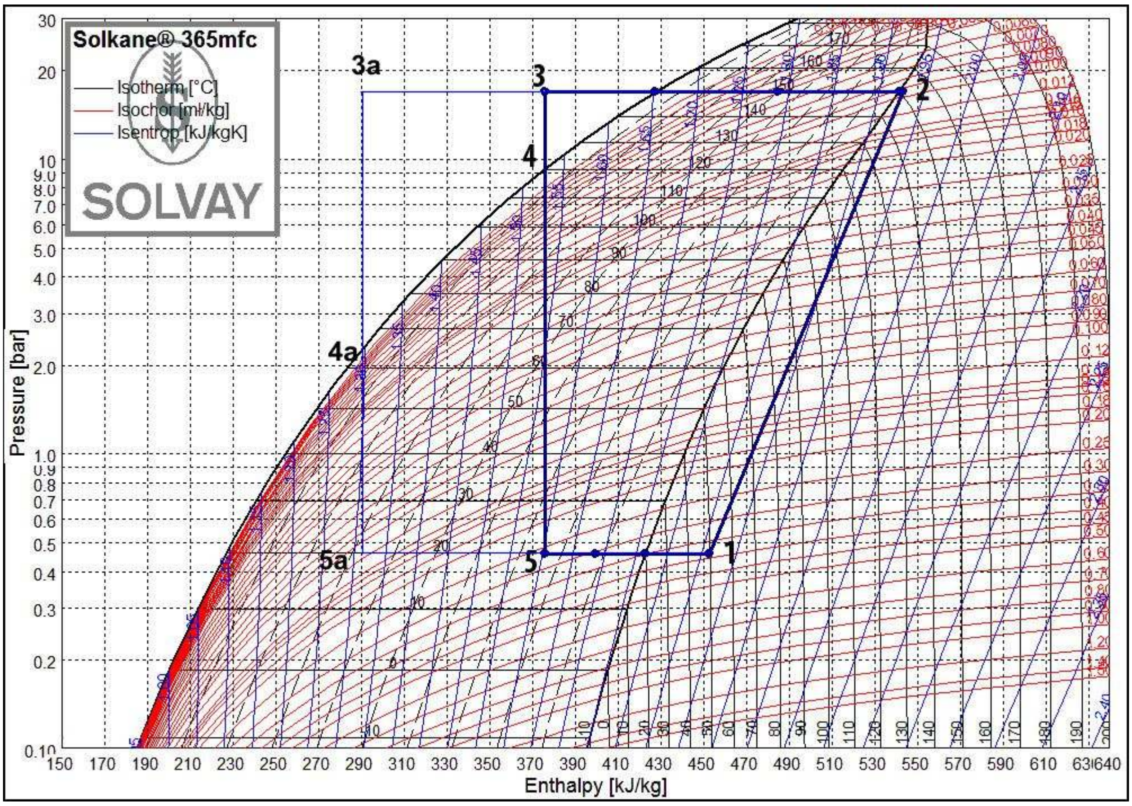

Fig. 8 Log p-h diagram for heat pump using for district heating

Fig. 9 shows the calculated price for district heating of city Novo mesto without investment costs.

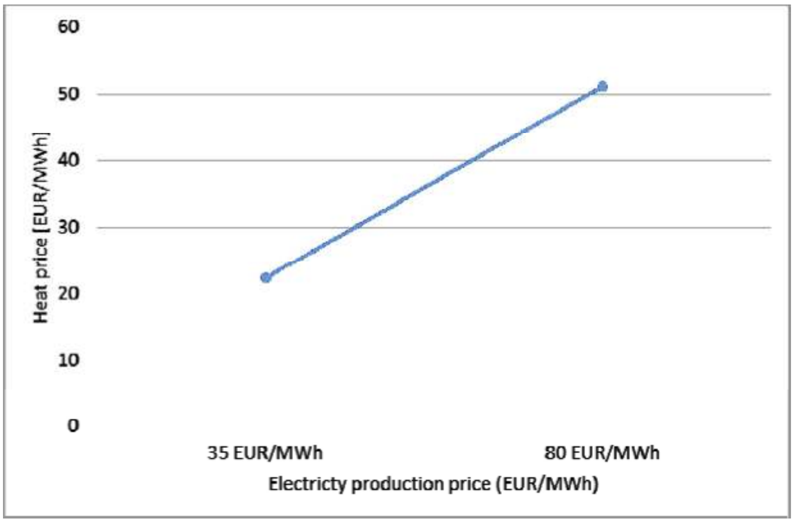

Fig. 9 Heat price for district heating with heat pump

5. Conclusion

This study shows the analysis for application of PWR nuclear power plant for district heating or hydrogen production. The analysis shows that hydrogen production or heat for district heating of city Novo mesto, including application of heat pump technology, are very interesting additional energy products in PWR nuclear power plant. In the presented article we have studied we have analyzed the production price for district heating and hydrogen production price in dependence of electricity production price (35-80 EUR MWh). The analysis shows that thermochemical CuCl process in combination with nuclear power plants produces very cheap hydrogen in comparison with nuclear electrolysis.

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