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Energy economic evaluation of solar and nuclear driven steam methane reforming processes

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ABSTRACT

Changing the high temperature heat supply of energy intensive industries from today's mostly fossil sources to nuclear or renewable sources offers the opportunity of massive reductions of greenhouse gas emissions. Even though the high temperature gas-cooled reactor (HTGR) as well as the solar tower is technically capable to supply heat at the required high temperature level, it is uncertain whether these technologies can compete with the fossil energy supply. Therefore, the aim of this paper is the assessment of the economic competitiveness of process heat supply by HTGR or solar tower to fossil fired processes using steam methane reforming as industrial example process. Applying a self-developed optimization model, energy economic analyses are conducted for nuclear, solar and fossil energy supply systems. The results are benchmarked with the Hydrogen Economic Evaluation Program (HEEP) of the International Atomic Energy Agency (IAEA) and compared to literature values. The analyses show that hydrogen generation costs of the solar tower system are higher than those of the HTGR system. Both technologies benefit from the support of a fossil heater, as the hydrogen generation costs can be significantly reduced even with a small amount of burned natural gas. Nevertheless, a steam methane reforming process run by HTGR or by solar tower is not yet competitive to the natural gas fired hydrogen production.

1. Introduction

The European Union together with other countries around the world agreed to reduce greenhouse gas emissions within national and international climate change objectives. In some countries structural changes in energy supply systems can be observed. Worldwide the process heat demanded by industrial plants has a significant share of primary energy consumption. Today, this heat, which is mainly needed at a high temperature level, is basically supplied by the combustion of fossil fuels accompanied by massive greenhouse gas emissions. CO_2-neutral or even CO_2-emission free alternatives to the fossil-derived process heat are offered by nuclear or renewable energy sources. Due to its high reactor outlet temperature, the high temperature gas-cooled reactor (HTGR) is capable to supply high temperature heat for industrial processes. On the renewable side the solar tower is suitable to reach the required high temperatures. Due to the high variety of energy demand structures of different industrial processes it is necessary to focus on an example process in order to analyze the nuclear and solar energy supply. Hydrogen production by steam methane reforming (SMR) is a widespread industrial process and therefore highly relevant for investigation. Although CO_2-neutral hydrogen production processes are under development, a transition in hydrogen production industry would most likely begin with a hybrid system like the solar or nuclear heated SMR (Giaconia et al., 2008; Möller et al., 2006). Even though the high temperature heat supply by HTGR or solar tower is technically possible, the real implementation of nuclear or solar energy supply systems on an industrial scale depends on the economic profitability. Therefore, energy economic analyses are needed to evaluate the economic competitiveness of process heat supply by HTGR or solar tower to fossil fired processes. For the reason of comparability, it is necessary to evaluate the three different supply systems with one method and consistent assumptions, since the results are highly dependent on the economic frame conditions.

2. System description

Hydrogen production processes can be divided into thermal processes, electrolytic processes and thermochemical cycles. Today, the principal sources for hydrogen are fossil fuels, and the process heat required for hydrogen production is basically coming from the

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combustion of the fossil fuels accompanied by the emission of climate affecting gases. The aim of this paper is the economic assessment of the solar and nuclear high temperature process steam supply and not the assessment of different hydrogen production technologies. Therefore, the state of the art SMR process is used as the example process. The economics of other hydrogen production technologies and their coupling to nuclear and solar heat are currently under investigation, for example by (Pregger et al., 2008; Bredimas, 2015; Harvego et al., 2008, 2010; Richards et al., 2006; EPRI, 2004).

2.1. Steam methane reforming

Steam reforming of natural gas (methane) is currently the most economical and mostly applied technology of hydrogen generation accounting for approximately half of the world's hydrogen generation. In the first process step, the natural gas/methane feed is desulfurized by usually employing a cobalt molybdenum catalyst where the sulfur compounds are hydrogenated to H_2S. The purified feed is then mixed in the reformer with superheated steam at pressures of 2.5–5 MPa and temperatures of about 800–900 °C and catalytically converted to a mixture of hydrogen, carbon monoxide, carbon dioxide, and residues of still unreformed methane. A high temperature, a comparatively low pressure and a steam/methane ratio of > 2 favor high conversion rates of methane. After cooling, the generated synthesis gas (H_2 + CO) can be converted in the water gas shift reaction to a mixture of H_2 and CO_2 which is raising the hydrogen output even further. Water that is not reformed is condensed. In the next step CO_2 is captured from the syngas either by a physical or a chemical absorption. In this paper a chemical absorption is assumed using monoethanolamine (MEA) as solvent. In the final step, the pressure swing adsorption, remaining amounts of methane and carbon monoxide will be removed eventually resulting in a hydrogen gas purity of 99.99 %. The efficiency of today's conventional large-scale reformer plants is about 74% (based on lower heating value or net calorific value, where latent heat of vaporization is ignored). In order to reduce greenhouse gas emissions the captured CO_2 can be compressed and stored. This significant reduction in CO_2 emissions, however, will be at the expense of an enhanced electricity consumption required for gas compression, thus reducing the overall efficiency (Möller et al., 2006; Verfondern, 2007; NFE, 1985).

2.2. High temperature reactor

According to the Gen-IV International Forum (GIF) the high temperature reactor is one of the most promising nuclear reactor concepts of the next generation (Gen-IV, 2002). It is expected to be further progressed in terms of safety and reliability, proliferation resistance and physical protection, economics and sustainability (Gen-IV, 2002). Characteristic features are a helium cooled, graphite moderated, thermal neutron spectrum reactor core with a reference thermal power production of up to 400–600 MW_{th}. Coolant outlet temperatures of 750–950 °C are ideally suited for a wide spectrum of high temperature process heat applications in various industries.

The combination of an external heat source with chemical processes will need a device to decouple the heat from its origin to the heat utilization system. In the case of a nuclear plant, it is the intermediate heat exchanger (IHX) to provide a clear separation between nuclear plant and heat application. Under normal operating conditions, the IHX prevents the primary coolant from accessing the process plant. Furthermore, the IHX prevents the processing gases from accessing the reactor containment, thus limiting or excluding a potential radioactive contamination of the product (e.g. by tritium). Furthermore, the physical separation allows for the heat application facility to be conventionally designed, meaning easy maintenance and repair works under non-nuclear conditions. The HTGR has three heat exchanging levels, from the primary side to an intermediate circuit, then to a heat delivery system of the chemical plant before being transferred to any chemical process.

The technology of the HTGR takes benefit of the broad experience from respective research projects in the past such as the German Prototype Nuclear Process Heat (PNP) project (Kubiak et al., 1993). But also HTGR operation like the HTTR in Japan and the HTR-10 in China (IAEA, 2014), as well as comprehensive research and development efforts which were initiated in many countries (for example by the US Next Generation Nuclear Plant Project (NGNP) (Bredimas, 2015)) since recently to investigate HTGR systems in connection with nuclear hydrogen production provide valuable knowledge.

The baseline concept for a German small modular HTGR is the electricity producing 200 MW_{th} HTR-Modul pebble bed reactor designed by the former German company SIEMENS-INTERATOM (Reutler and Lohnert, 1984). It is characterized by a tall and slim core which ensures — in combination with a low power density — that even in hypothetical accidents, the release of fission products from the core will remain sufficiently low to cause no harm to people or the environment. Consequently, a process heat variant of the HTR-Modul reactor has been developed, of which the principal cornerstones are a thermal power of 170 MW and a helium outlet temperature of 950 °C to deliver process heat for the SMR process (Gesellschaft für Hochtemperaturreaktor-Technik MBH, 1981). Without employing an IHX (which was deemed feasible and licensable at that time), the hot helium coolant is directly fed to the steam reformer which consumes 71 MW_{th}, and to the steam generator operated with 99 $MW_{th.}$ From the total heat transferred into the steam reformer, 85% are used for the reforming process, while 15% are taken to heat up the feed gas. Partial load conditions of the steam reforming process can be regulated by changing the feed gas flow. A requirement, however, is a constant product gas quality, i.e. the composition should remain constant, which can be accomplished by maintaining a constant reforming temperature.

The energy economic analyses in this paper are conducted for a modular pebble bed 250 MW_{th} reactor with a reactor outlet temperature of 850 °C. The reactor size corresponds to one reactor module of the Chinese HTR-PM project.

2.3. Solar tower and thermal storage

Solar energy can be converted to usable thermal energy by employing solar thermal plants that operate with concentrating collector devices. High temperature solar thermal systems are suitable to generate electricity in the range of 10–1000 MW and to deliver process heat of 1000 °C or higher to produce saturated or superheated steam for steam turbine cycles or compressed hot gas for gas turbine cycles. Such systems are able to provide virtually CO_2 emission free energy for hydrogen generation (Müller-Steinhagen, 2013).

Different technologies have been developed for concentrating the solar insolation in order to produce steam or hot air. Concentration of solar radiation can be done through line concentrators or point concentrators. Temperatures of line concentrating systems like parabolic trough or Fresnel systems are limited to about 600 °C and therefore not suitable for process heat applications requiring temperatures of 800 °C and higher. Point focusing systems on the other hand can reach the required high temperature level. These systems include dish-engine systems and solar towers. As dish systems have normally a low power range of about 5–50 kW, they seem unsuitable for large scale industrial applications. The solar tower is suitable to reach temperatures of over 1000 °C and is, unlike the dish system, suitable for application in the high MW-range. Since this technology seems to have the best chance of an industrial application amongst the solar heat supply systems, it is further investigated in this paper (Stoddard et al., 2006; Heimsath, 2009).

Several hundreds of tracked and typically slightly shaped mirrors, so-called heliostats, are arranged around a tower. They redirect and concentrate solar radiation to one spot on top of the tower where the radiation is collected. The solar energy is absorbed by a working fluid