Energy Strategy Reviews 18 (2017) 157–174

Contents lists available at ScienceDirect

Energy Strategy Reviews

journal homepage: www.ees.elsevier.com/esr

A regional technology roadmap to enable the adoption of CO2 heat pump water heater: A case from the Pacific Northwest, USA

Momtaj Khanam, Tugrul U. Daim*

Portland State University, Portland, OR, USA

ARTICLE INFO

Article history:
Received 12 February 2017
Received in revised form
16 June 2017
Accepted 27 September 2017

Keywords:
Technology roadmap
Technology adoption
Water heater
Heat pump
Regional strategy

ABSTRACT

The quest for home energy products that would reduce electricity bills, avoid kilowatt-hours of electricity generation, and minimize carbon footprint has sparked the innovation of many energy efficient technologies. The CO2 heat pump water heater (HPWH) is one such innovation led by Japan, the technology leader of the Pacific Rim. The product was developed over the last decade, and many countries have configured the technology to local needs due to the benign nature and high efficiency potential of the technology. However, CO2 HPWH has yet to enter the Pacific Northwest market. Hence, a detailed roadmap needs to be outlined for the replacement of the existing less efficient water heaters and the integration of the CO2 HPWH technology in the region. The Bonneville Power Administration (BPA), has been relentlessly working towards energy efficiency as one of its many community outreach programs. The CO_2 Heat Pump Water Heater is one of a kind project initiated by the BPA in collaboration with the Northwest Energy Efficiency Alliance (NEEA). With guidance from experts at BPA, NEEA, the Energy Trust of Oregon, the Pacific Northwest National Laboratory, and other stakeholders, an "action plan" has been developed focusing on CO2 refrigerant technologies for heat pump water heater applications. The project identifies where opportunities exist in the coming years for specific actions to be taken in the areas of emerging technologies research, utility program development, market research, and related activities to help increase regional adoption of these energy-efficient systems. The roadmap has given some interesting insights. Projects are undertaken for improving the efficiency of components and equipment technology. Extensive testing and measure development initiatives are headed towards facilitating enactment of law or regulation. However, cost is one of the most important aspect in adoption of the technology and utilities and other stakeholders needs to come forward in incentivizing the project.

1. Introduction

Electric resistance water heaters are used in the majority of the Pacific Northwest homes. Electric water heaters are inefficient, costly, and carbon intensive. Hence, high efficiency water heaters designed for the NW climate would save enormous energy. Energy efficient water heaters have the prospect of saving nearly 500 aMW by 2029, and are capable of powering 381,500 homes each year [64]. Carbon dioxide (CO2) has low global warming potential (GWP) when compared to other refrigerants, has zero ozone depletion prospective, and is not flammable and non-corrosive [54]. As a member of the Montreal Protocol, the U.S. must gradually decrease Hydro chlorofluorocarbon (HCFC) consumption and production, leading to a complete HCFC phase-out by the year 2030. Moreover, the new efficiency standard set by the Department of Energy (DOE), and effective as of April 16th, 2015, requires large-capacity electric water heaters to possess 200% Coefficient of Performance (COP), a standard that can only be achieved by HPWH [15]. For HPWH, the efficiency is expressed by Coefficient of Performance (COP), a numerical value calculated by considering useful energy output from the water heater to the total energy input to the device [63].

With this end in view, several organizations in the Pacific Northwest are working towards adoption of the technology in the region. NEEA (Northwest Energy Efficiency Alliance) is an alliance of more than 140 Northwest utilities and energy efficiency organizations representing more than 13 million energy consumers. The Regional Emerging Technology Advisory Committee (RETAC) is the committee that provides Northwest Energy Efficiency Alliance (NEEA) advice, experience, and feedback to enhance the adoption of emerging technology in the regional market. The Bonneville

* Corresponding author.
E-mail address: tugrul.u.daim@pdx.edu (T.U. Daim).

https://doi.org/10.1016/j.esr.2017.09.019
2211-467X/

Power Administration (BPA) is yet another organization at the Pacific Northwest that actively participates and collaborates with NEEA in energy efficiency projects in the region. BPA is a federal nonprofit agency that sells wholesale electric power. CO2 HPWH has been recognized as one of the preferred technology in RETAC's priority list of technologies that could lead to increased energy saving. Also, CO2 HPWH is one of BPA Energy Efficiency Emerging Technology (E3T) team's top technology research areas, recognizing its potential in harnessing regional collaboration for energy efficient technology development.

Refrigerants have long been branded as a major contributor in tampering Earth's protective ozone layer. Also, they have high Global Warming Potential (GWP) [10]. The most common refrigerant that has been used for a long time is HCFC−22 (R -22), a hydro chlorofluorocarbon. However, as an initiative to gradually phase out the use of R-22, the Montreal Protocol requires the U.S. to reduce its consumption of HCFCs by 99.5% below the U.S. baseline by 2020. Even if the recovery, recycling, and reclamation to service existing systems beyond 2020 would be allowed, production would be banned for servicing existing air conditioners and heat pumps [26]. Besides, an amendment to the Montreal Protocol initiated in October, 2016 ties 197 countries by their commitment to reduce production and consumption of HFCs by 80% within 30 years period [27]. European Union also enacted new regulation since 2015 that overrides the first F-gas (Fluorinated gases) regulations adopted in 2006. According to this ambitious Act, F-gas emission is to be cut by two-thirds of the 2014 levels by the year 2030 and reduction to the extent of 80−95% from 1990 level by the year 2050 [28]. Concerns with HCFC and HFC refrigerants have led to the invention and discovery of non-ozone depleting alternatives that have lower GWP.

Carbon dioxide used to be the working fluid for actuating machines during the mid-nineteenth century. It was superseded by chlorofluorocarbons (CFCs) that operated at much lower pressures. Carbon dioxide kept a low profile as it was only used in cascade systems for industrial and process applications. However, in recent years it returned with new vigor due to its inherent physical properties that make it ideal for applications in vapor compression refrigerating machines and heat pumps [69].

The phase diagram of CO2 is unique compared to other refrigerants with its high triple point (coexistence of solid, liquid and gaseous phase) and low critical point (point above which there is no discrete liquid or gaseous phase as both phases have identical physical properties manifested in temperature, pressure and volume or density) as shown in Fig. 1 [24]. The refrigeration cycle occurs between subcritical and supercritical pressure and is known as transcritical [13]. The process begins with compression in a compressor that increases the temperature as high as 130 °C. In the gas-cooler heat dissipates at a constant pressure above the critical point. Temperature changes from the inlet to the outlet of the cooler but there is no change in phase as temperature and pressure do not impact at the supercritical region. As the gas cools the temperature changes but the pressure remains the same. The supercritical fluid passes an expansion valve at a constant enthalpy. The output from the expansion is a liquid-vapor which passes through an evaporator at a constant pressure lower than critical. The output from the evaporator enters the compressor at a slightly higher temperature and the cycle repeats. The gas cooler pressure affects the refrigeration capacity and compressor power consumption which in turn impacts the Coefficient of Performance (COP) of the device [21]. Coefficient of performance (COP) for heating is the heat output to compressor performance [5]. The reason for a high COP by CO2 refrigerant is due to the high temperature difference known as “glide” that can be achieved at the inlet and outlet of the gas cooler compared to what can be achieved in a condenser for a conventional refrigerant. For different operating conditions, there are optimal gas cooler pressures that lead to maximum COP. The expansion valve and the low pressure device (LPD) are some design features for HPWHs that helps to achieve maximum COP by optimizing the gas cooler pressure in varying conditions [75].

The first CO2 HPWH with the pet name “EcoCute” was developed in Japan. It was introduced to the Japanese market in the year 2001. The “EcoCute” technology is a product of extensive collaboration among research institutes, electric power industries, manufacturers, and government entities with a common passion for saving energy and reducing greenhouse gas emission [48].

A heat pump or a refrigerator works on the same principle even if they have different deliverables. In a refrigeration cycle heat is extracted from inside the refrigerator (source) by an evaporator which produces a high-pressure and high-temperature gas. The heat is dissipated to the outside environment (sink) by a condenser. On the other hand, in a heat pump water heater, heat is extracted from the environment (source) by an evaporator. The heat produces a high-pressure, high-temperature gaseous refrigerant. The pressure and temperature is further increased by a compressor. While passing through a condenser the heat is transferred to water (sink) to produce hot water. Hence, in a refrigerator heat is extracted from inside the cold atmosphere and given out to the warmer room environment while in heat pump, heat is extracted from cold atmosphere and released in warmer room temperature [53]. A pump becomes efficient when evaporation of refrigerant occurs at a low temperature [30].

The steps of how a HPWH works are illustrated below:

1. Liquid refrigerant passes through an evaporator where it extracts heat from the air and turns into gas.
2. An electric compressor compresses the gas refrigerant. Temperature rises due to compression of the gas.
3. The hot gas dissipates heat to water while it flows into a condenser. The gas returns to liquid form when temperature falls in an expansion valve.

The CO2 heat pump water heater uses CO2 as the working fluid. The use of natural refrigerant CO2 helps to achieve total efficiency higher than that of combustion boilers [77].

The main components of a CO2 refrigeration cycle are compressor, gas cooler (instead of a condenser), internal heat exchanger, expansion valve, evaporator, and low-pressure receiver. The steps in working of a CO2 HPWH are outlined below [74].

1. The CO2 refrigerant absorbs heat from the air and transfers it to the heat exchanger (for air), then delivers the heat to refrigerant.
2. Warmed up CO2 is pressed by a compressor and becomes hotter.
3. Heat of the refrigerant is transferred to water by a heat exchanger (for water) to produce hot water.
4. The refrigerant after losing heat returns to the heat exchanger (for air) again.

2. Literature review

The term “roadmap” was first coined during the mid-nineteenth century to denote roads in a particular area. However, it found a new connotation when it was used in conjunction with technology. Motorola CEO, Robert Galvin, identified and invented Technology Roadmapping (TRM) in the 1970s as a tool that recognizes the different capabilities required today to achieve a certain technology in the future [73]. Since its inception, the concept has been adopted, adapted, and implemented in many different organizations