USE OF HYDROGEN FROM RENEWABLE ENERGY SOURCE FOR POWERING HOT-MIX ASPHALT PLANT

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Abstract: A significant portion of paved roads and highways are surfaced with Hot-Mix Asphalt. Environmental Life-Cycle Assessment studies have shown that, in the production of Hot-Mix Asphalt pavements, major consumption of energy takes place during asphalt mixing and drying of aggregates, more than what is consumed during the extraction of crude oil and the distillation of bitumen. Currently, natural gas is the primarily source of fossil fuel used to produce 70 to 90 percent of the Hot-Mix Asphalt in the USA, while the remainder of the Hot-Mix Asphalt is produced using oil, propane, waste oil, or other fuels. Energy-related CO_2 emissions resulting from the use of fossil fuels in various industry and transportation sectors represent a significant portion of human-made greenhouse gas emissions. This study investigates the technical feasibility of using a hybrid wind energy system as a clean source of energy for operating an entire Hot-Mix Asphalt production facility. Since wind blows intermittently, the extracted wind energy will be stored in the form of hydrogen which is considered a lightweight, compact energy carrier, for later use, thus creating a ready source of electricity for the Hot-Mix Asphalt plant when wind is not present or when electricity demand is high.

Keywords: Hot-Mix Asphalt (HMA), renewable energy, greenhouse gas emissions, hydrogen, wind.

1. Introduction

Hot-Mix Asphalt (HMA) mainly consists of a mixture of aggregate and asphalt binder (or bitumen) and is primarily used for surfacing roads, airport runways, parking lots and driveways. About 95% of the total weight of an asphalt pavement is composed of aggregates. In the US alone, there are over 4,000 asphalt mix facilities producing 500 million tons of asphalt pavement material annually (NAPA, 2011).

According to the process by which the liquid asphalt and aggregate are mixed, modern HMA facilities can be broadly classified as either drum mix plants or batch mix plants (Scherocman et al. 1988). In the production of HMA, it is very important to heat the asphalt binder (which remains solid at ambient temperatures) to between 135 and 163 °C (275 and 325 °F) before it is sprayed on the aggregate (Brown et al. 2009). In addition, the aggregate must be dried and heated to remove the moisture so that they can be fully coated with the heated asphalt binder.

The primary difference between the two types of plants is that the batch mix plants produce HMA in batches one at a time whereas the

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drum mix plants produce HMA continuously which can be stored up in heated storage silos for several days. Further, a drum mix plant uses a rotary dryer to dry the aggregate which is then mixed with the liquid asphalt binder in the same vessel in a drum mix plant. In a batch mix plant, on the other hand, the aggregate is dried first separately in a rotary dryer (similar to that used in drum mix plant) and then mixed with the liquid asphalt binder in a mixer. The mixed HMA is generally stored in a silo or storage bin temporarily and then emptied into haul trucks for transporting the material to the job site (Brown et al. 2009).

Schematic diagrams depicting the process flow for a typical batch mix plant and atypical drum mix plant are displayed in Fig. 1 and Fig. 2, respectively. Since, the drum mix plants mix the hot asphalt and the dried aggregate in the same vessel eliminating the need for hot aggregate screens, hot bins and a pugmill mixer, they reduce capital costs and minimize uncontrolled particulate emissions from the dryer (Beachler et al. 1983).

Sustainability is a key issue facing today's society and arguably the hottest topic of the moment. Highway agencies, engineers, and

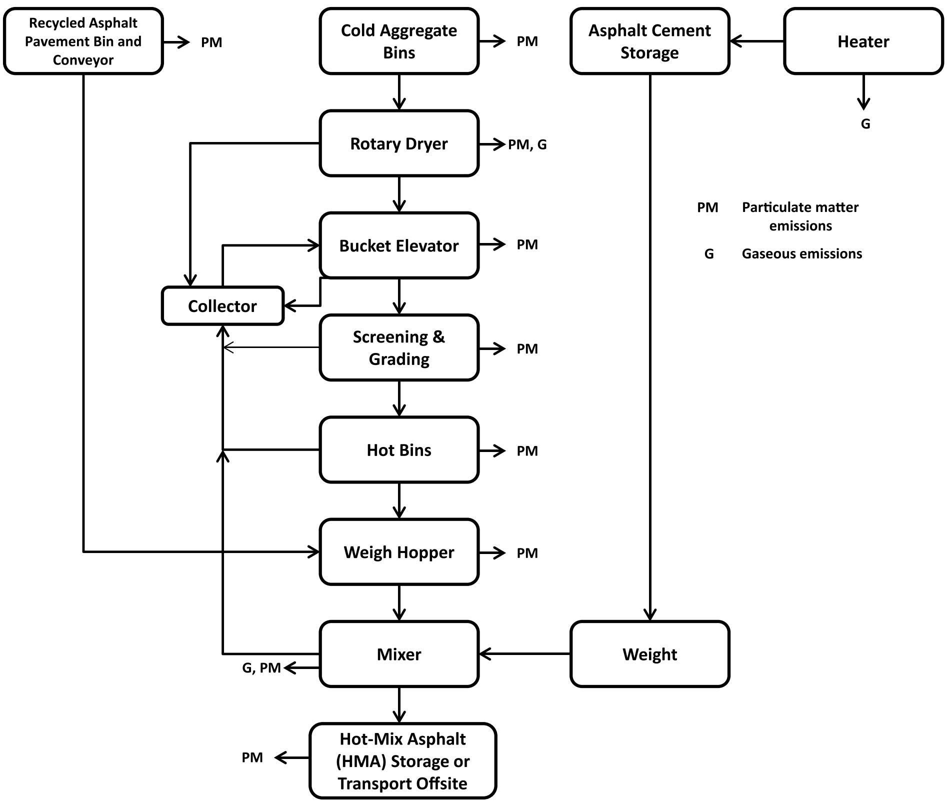


Fig. 1.
Schematic of Process Flow in Batch Mix Asphalt Plants
Source: NPI (1999)

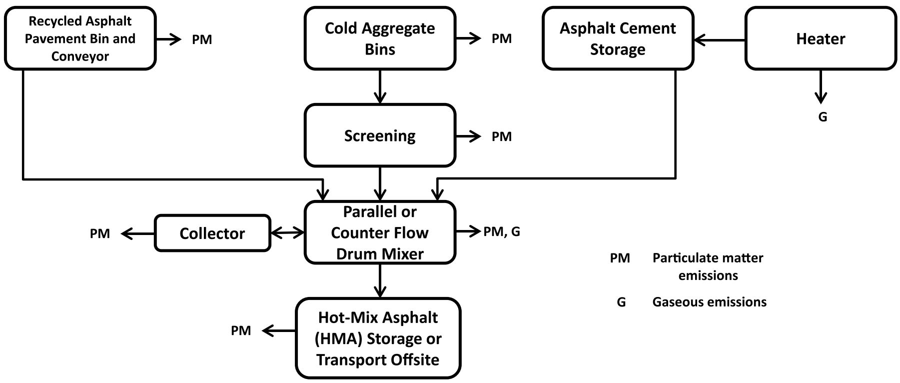


Fig. 2.
Schematic of Process Flow in Drum Mix Asphalt Plants
Source: NPI (1999)

the industry are also rising to the occasion by actively promoting sustainability-oriented engineering practices and projects (Gopalakrishnan, 2011). Terms like green highways, sustainable pavements, carbon footprint, environmental Life-Cycle Assessment (LCA) etc. are beginning to make increased appearances in transportation literature, and in the titles of conferences and peer-reviewed journal special issues.

Over the past three decades, advancements in technology and increasing concern for the environment and human health combined with economic sustainability have resulted in HMA facilities generating significantly lower levels of dust, smoke, odors, and noise. The US EPA delisted HMA facilities from the MACT (Maximum Available Control Technology) standard in February 2002 as they were not considered major sources of air pollutants (Astec, Inc. 2011). The HMA industry is constantly seeking innovative means and developing new technologies to improve fuel economy and minimize emissions during mix production and paving operations (Moray et al. 2006; Davis, 2010).

This paper investigates the feasibility of using wind energy stored in hydrogen fuel cells as a clean source of energy for operating an HMA production facility (especially focusing on the major energy consumers related to heating and drying the aggregate, etc.). Wind power is growing steadily as an alternative source of energy as well as a renewable source of power generation driven by escalating fossil fuel prices, wind energy technology improvements, impending regulatory constraints on coal-fired power plants and increasing public preference for renewable energy (Logan and Kaplan, 2008).

In the proposed innovation, a wind mill installed at the HMA mix facility will harness wind energy and will be stored in the form of hydrogen which is considered a lightweight, compact energy carrier for later use. The wind energy is converted into electricity in the wind mill generator for powering the HMA plant. The excess wind energy is diverted to an electrolyzer to generate hydrogen, which is then stored in a hydrogen storage bed. The stored hydrogen energy will then act as a ready source of electricity for operating the HMA plant when wind is not present or when electricity demand is high.

Nomenclature

A	swept area of the rotor blades (m^2)
C_p	performance coefficient
$\dot{n}_{el}$	rate of electrolyzer production in the electrolyzer (mol/s)
$\dot{n}_{fc}$	rate of hydrogen consumption in the fuel cell (mol/s)
P_{el}	electrical power consumed by the electrolyzer (W)
P_{fc}	power generated by the fuel cell (W)
P_{avg}	power generated by the wind turbine (W)
R	radius of the rotor blades (m)
v_w	upstream wind velocity (m/s)
λ	tip speed ratio
ρ	density of air (kg/m^3)
θ	pitch angle
ω	rotational speed of rotor blades (1/s)
η_{el}	efficiency of the electrolyzer
η_{fc}	efficiency of the fuel cell
ΔH_c	heat of combustion of hydrogen (J/mol)

2. Major Components of a HMA Facility

The components of a HMA mix facility which consume significant energy are examined little more in detail in this section. As seen in Fig. 1 and Fig. 2, the common components in both batch and drum mix plants include the following (NAPA, 2011):

- Cold feed bins which meter the right amount of aggregates (stored in stockpiles or large silos) used in the mix to the drying drum
- Asphalt binder storage tanks
- Dryer drum which dries and heats aggregates by tumbling them through hot air (a counter-flow drum means that the aggregates move in the opposite direction as the hot air)
- Emission or Environmental control system of which baghouse is a major component which traps and removes fine sand and dust particles and returns them to the mix
- Storage silos which are insulated and may be heated to prevent heat loss

Thus, the primary energy consumers associated with HMA production are the dryers, hot bins and mixers (batch mix plants), and liquid asphalt cement storage system. Energy is also required to heat the storage silos to temporarily hold the HMA as well as the asphalt storage tanks. For the sake of simplicity, the focus is on drum mix plants in this paper although similar principles can be extended to other plant types.

2.1. Drum Mix Plants

A drum mix plant (Fig. 3) has a number of components which can be divided into the following broad categories (Scherocman et al. 1988):

- Aggregate handling system
  - Cold feed bins; gathering and charging conveyors; weigh bridge and belt speed sensor; mineral filler system (if any); and dust return system (if any)
- Asphalt cement storage and processing system
  - Heated storage tank (to hold the liquid asphalt cement until needed); and pump and meter (to proportion and transfer the asphalt cement to the plant)
- Blending system
  - Drum mixer
- Other drum mix plant components
  - HMA charging conveyor; HMA surge silo; plant dust collection system; control station (to monitor the flow of aggregates, asphalt cement, and HMA).

The drum mixer (or dryer drum) consumes significant energy since its function is to produce HMA that is uniformly coated and is at the desired temperature by drying and heating the aggregates delivered from the cold feed bins and mixing them with the liquid asphalt cement (Brown et al. 2009). While the drum production rate is largely a function of the drum diameter, the aggregate "dwell time" (the time it spends in the drum) is influenced by a number of factors including the drum length, drum angle, rotational speed of the drum, design and number of flights (metal parts or vanes bolted/welded to the inner drum circumference to control the aggregate movements), and the size of the aggregate (Brown et al. 2009). It should be noted that the variation in the moisture content of aggregate stockpile can affect the energy consumption of the drum mixer considerably (Brown et al. 2009). The two commonly used drum mixer designs include the parallel-flow and the counter-flow design (Fig. 4). In parallel-flow drum mix plants, the sized aggregate enter the dryer drum at the burner end, the aggregate and air flow move in the same direction (along with the combustion products) and the HMA is discharged at the opposite end. In the counter-flow drum, the burner is located near the HMA discharge end of the drum, the aggregate is introduced at the opposite end of the burner and thus the aggregate and air flow (along with the exhaust gases) move in opposite directions (Scherocman et al. 1988; Brown et al. 2009). The unitized counter-flow drum (or double barrel drum) utilizes a counter-flow dryer as an "inner" drum and a larger diameter "outer" drum forms a mixing chamber (WAPA, 2010).

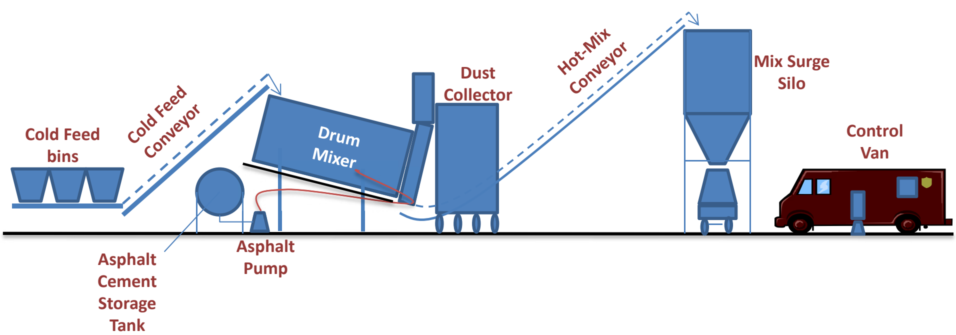


Fig. 3.
Major Components of a Drum Mix Plant
Source: Brown et al. (2009)

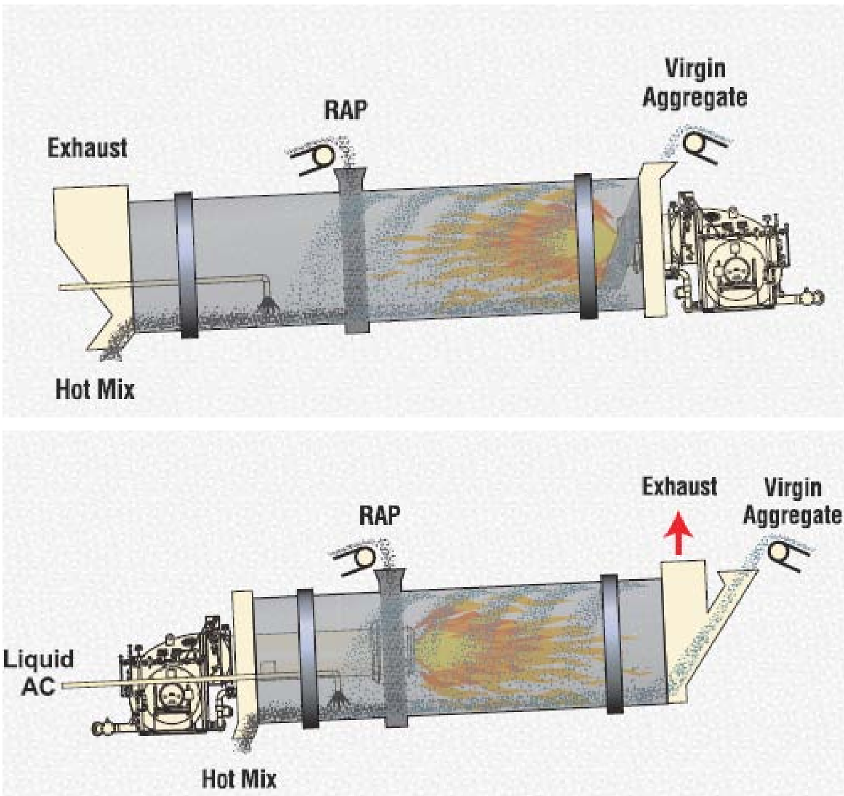
In recent years, the counter-flow drum mix design is more preferred by the HMA industry since they supposedly use less fuel and generate lower hydrocarbon emissions than parallel-flow drums (Astec, Inc. 2011). Since the mixing of liquid asphalt cement and virgin aggregate (and/or RAP) are done in a zone away from the exhaust gas stream in a counter-flow drum mix plant, it is likely to have lower organic emissions than parallel-flow drum mix plants (US EPA, 2004). However, the existing data has been reported to be insufficient to discern significant emissions differences between the two process designs (US EPA, 2004).

3. Proposed Hydrogen Powered HMA Plant

3.1. Typical Electricity Requirements of a HMA Plant

During typical HMA plant process operations, the maximum electricity consumption is less than 500 kW/hr and 20 to 50 kW/hr at other times (NPI, 1999). Dryer burners are typically designed to operate on almost any type of fuel, including natural gas, LPG, light fuel oils and waste fuel oils.

Table 1 shows the typical energy requirements



(a) (b)

Fig. 4.
Drum Mixer Designs: (a) Parallel – Flow Drum Mixer; (b) Counter – Flow Drum Mixer
Source: Mize, Renegar (2009)

of a HMA plant taken from *The Encyclopedia of Chemical Processing and Design* (Asphalt Institute, 1983). Although this reference may be a bit outdated, it is still used because it provides comprehensive information related to HMA production energy requirements. The HMA production capacity of the drum mix plant is assumed to be 180 Mg/hr or 200 (TPH) (Asphalt Institute, 1983). Existing typical drum mix plants can produce over 270 Mg/hr (300 TPH) of HMA (Astec, Inc. 2011). Again, the numbers from the older reference is used for the sake of maintaining consistency. Also, the goal of this paper is to demonstrate the proposed concept using available data and reasonable engineering assumptions.

Table 1
Energy Requirements of a Typical HMA Drum Mix Plant Operation

Production Unit	Value	Units
HMA Production Capacity	200 (180)	t/hr (Mg/hr)
Asphalt Storage	6400 (7.44)	BTU/t (MJ/Mg)
Cold Feed	4730 (5.50)	BTU/t (MJ/Mg)
Dryer Drum and Exhaust	4770 (5.55)	BTU/t (MJ/Mg)
Asphalt Pump Storage Conveyor	650 (0.75)	BTU/t (MJ/Mg)
* Note: 1 ton (T) = 0.90718474 Mega – grams (Mg); 1 BTU = 1055.05585 Mega – Joules (MJ)		

Source: Asphalt Institute (1983)

The asphalt storage requires energy to keep the liquid asphalt cement at a temperature of 315 °C (600 °F). The multi-compartment cold feed needs energy for proportioning the required aggregate and transporting them to the gathering and charging conveyors. The asphalt storage conveyor requires energy to keep the conveyor belt in motion. The use of renewable energy sources to power the HMA plant can significantly cut down the grid power consumption or even eliminate the usage of grid power depending on the nature and reliability of the renewable energy source. The use of wind energy to power a HMA plant is explored in this paper. However, wind energy being intermittent in nature, requires a good storage technology to ensure reliable power supply. The most reliable storage technologies reported in the literature are compressed energy storage (Hoffeins, 1994; Hounslow et al. 1998; Khaitan and Raju, 2011b; Raju and Khaitan, 2012b), hydro power storage (Lerch, 2007), hydrogen storage (Ipsakis et al. 2009; Raju and Khaitan, 2011a; Khaitan and Raju, 2011a), and batteries (Wang et al. 2008). Compressed energy storage and hydro power storage requires specialized geographical features for its technical feasibility. Batteries are most suited for small scale storage. Hydrogen storage is most promising for medium scale storage application like that of a HMA plant. Raju and Khaitan (2011a) demonstrated the technical feasibility of hydrogen storage application for a residential application.

3.2. Overview of Hydrogen Storage Based Wind Energy System

The proposed hydrogen based renewable energy source for powering the HMA plant has two primary advantages. First is the use of readily available wind energy. This will reduce (or eliminate) the electricity consumption from the conventional power grid and the use of fossil fuel for drum mixer operations. Second is that hydrogen is considered a completely clean fuel with no pollutant emissions. This will greatly reduce the emissions from the drum mixer operation. This will greatly compliment other energy-efficient and emission-reduction technologies being implemented in asphalt plant facilities. Fig. 5 displays the overall conceptual schematic of a hot-mix asphalt plant powered by hydrogen based wind energy source.

In the proposed innovation, a wind turbine is installed at the plant site. Excess wind energy can be stored in the form of hydrogen and reused later to generate electricity using a fuel cell when needed. Whenever the wind blows, the wind turbine rotates and generates electricity. The generated electric power is routed to meet the demands of the electric load in the plant. Since, wind is intermittent, there will be periods of excess wind power and there will be periods of deficit wind power. Whenever there is excess electric power generation, it is rerouted to the electrolyzer to produce hydrogen. This hydrogen is then stored in hydrogen storage tanks. Two separate modules of hydrogen storage tanks are provided - one for charging and the other for discharging. When required, hydrogen is discharged from the discharge tank. The discharged hydrogen is routed to the drum mixer and the fuel cell stack. The drum mixer uses hydrogen as the fuel for the burner instead of fossil fuels like fuel oil, natural gas, etc.

The burner is a very critical component in the drum mixer whose function is to burn the fuel (combustion) to generate energy for heating the aggregate and evaporating the moisture from the aggregates as well as heat the HMA to the desired discharge temperature. A hybrid burner is employed in most HMA facilities, which includes both forced air and induced draft features for pulling the combustion air into the burner. Note that the temperatures exceed 1371 oC (2500 oF) at the tip of the burner flame. Efficient operation of the burners is crucial for economical production of HMA (Brown et al. 2009).

In the proposed application, both compressed air and hydrogen are sent into the combustion chamber of the drum mixer to produce superheated steam along with excess air. This superheated steam is used for drying the asphalt mixture. Hydrogen passed to the fuel cell is used to produce electricity. Fuel cell supplies electricity whenever there is deficit power generation from the wind turbine. The electricity source (wind turbine or fuel cell) is completely free of any pollutant emissions. In a

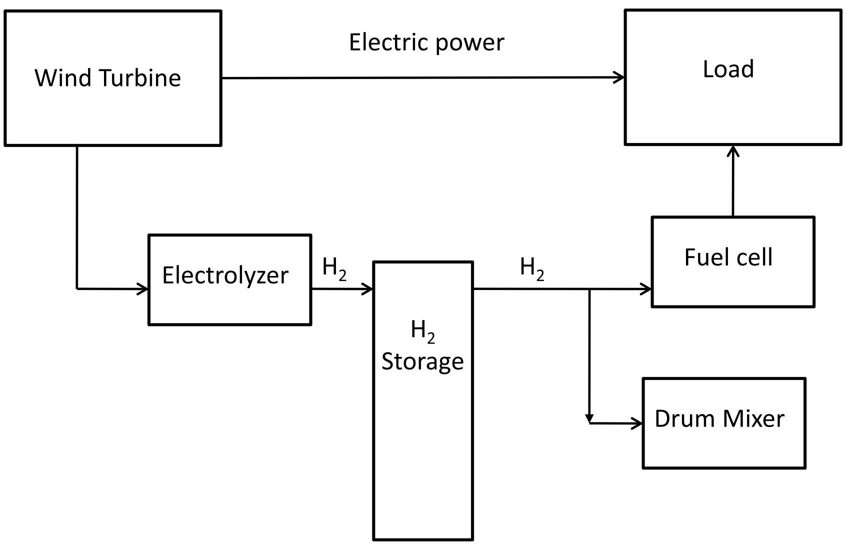


Fig. 5.
Overall Schematic of a Hot – Mix Asphalt Plant Powered by Hydrogen Storage Based Wind Energy

conventional HMA plant, on the contrary, the electricity is met by the grid power, which is a source of pollution (at the source) if it based on coal or natural gas plant. The next section deals with the description of the different components involved in the hydrogen storage based wind energy plant and estimation of the capacities of each of the components for a typical operation of HMA plant.

3.3. Wind Turbine

The estimate of the individual components of the hydrogen storage based wind energy source is based on data summarized in Table 2.

The following equations are used for the estimation of the capacities of the individual components.

Table 2
Estimated Capacities of Individual Components of Hydrogen Storage Based Wind Energy System

Component/Description	Value	Units
Hydrogen needed for drum mixer operation	6,932	mol/hr
Wind energy diverted to fuel cell for asphalt storage	3,751,111	kJ/hr
Wind energy diverted to fuel cell for cold feed	2,772,306	kJ/hr
Wind energy diverted to fuel cell for asphalt pump	380,972	kJ/hr
Load demand on the fuel cell	2,485,580	kJ/hr
Wind energy delivered to electrolyzer	8,200,867	kJ/hr
Wind Turbine		
Wind mill efficiency	0.4	
Wind mill capacity	5.695	MW
Electrolyzer		
Single electrolyzer capacity	1.2	kW
Number of electrolyzers	1900	
Fuel cell		
Single cell fuel cell capacity	2	kW
Number of fuel cells	485	
Hydrogen Storage (assume 12 hr continuous operation w/o charging)		
Hydrogen consumption rate	13.361	g/s
Maximum hydrogen storage capacity	577	kg

The power generated by the wind turbine is described as follows (Burton et al. 2011):

$$P_{avg} = \frac{1}{2}\rho C_p A v_w^3 \tag{1}$$

The performance coefficient C_p is given as (Burton et al. 2011):

$$\mathrm{C}_p(\lambda,\theta) = 0.73\ (\frac{153}{\lambda_i} - 0.38\theta - 0.002\theta^{2.14} - 13.2)e^{-\frac{18.4}{\lambda_i}} \tag{2}$$

$$\lambda_i = \frac{1}{\lambda - 0.02\theta} - \frac{0.003}{\theta^3 + 1} \tag{3}$$

$$\lambda = \frac{\omega R}{v_w} \tag{4}$$

The performance coefficient has a maximum value of 0.59. Raju and Khaitan (2011a) present wind model simulation subjected to a turbulent wind velocity profile. In the case of a turbulent wind velocity fluctuation, the wind power fluctuates rapidly.

3.4. Electrolyzer

The electric power supplied is converted into chemical energy in the form of hydrogen production. The amount of hydrogen produced is given by Eq. (5):

$$\dot{n}_{el} = \frac{P_{el}\eta_{el}}{\Delta H_c} \tag{5}$$

The efficiency of the electrolyzer is usually around 0.4-0.7 (Raju and Khaitan, 2011a). A value of 0.5 is used in this paper. The rest of the energy is reflected as the increase in thermal energy of the system. Adequate cooling has to be provided to maintain the temperature of the electrolyzer at its operating temperature. A number of electrolyzer units can be provided to produce hydrogen from the excess wind energy.

3.5. Fuel Cell

In the fuel cell, the chemical energy is again converted back into electrical energy. PEM fuel cells are best known for their efficiency. Fuel cell models are available in the open literature (Pukrushpan et al. 2004). The electric power generated in the fuel cell is given by Eq. (6):

$$P_{fc} = \eta_{fc}\dot{n}_{fc}\Delta H_c \tag{6}$$

The efficiency of the fuel cell is in the range of 0.4-0.7 (Khaitan and Raju, 2011a). A value of 0.5 is used in this paper. Table 2 summarizes the estimates of the individual components based on Table 1. The estimates are based on their maximum capacity under the assumption that all the wind energy is diverted to the electrolyzer and all the energy requirements are met either by combustion of hydrogen or by the fuel cell. Hydrogen being a light gas, occupies significant volume at ambient conditions. For example, to store 5 kg of hydrogen (roughly equivalent to 5 gallons [~10 liters] of gasoline in term of energy content) requires approx. 62 m^3 at 1 bar and 300 K. Hence, there is a need to store it more compactly to make it a viable option for practical operation. The storage of hydrogen is a bottleneck in this system. There are different hydrogen storage technologies currently available. The commonly known methods are compressed gas storage (Woodfield et al. 2008), cryo-compressed storage (Aceves et al. 2010), liquid hydrogen storage (Ahluwalia and Peng, 2008), absorption in heavy metal hydrides (Raju et al. 2010), complex metal hydrides (Ahluwalia, 2007; Raju and Kumar, 2011b; Lozano et al. 2009; Raju and Kumar, 2011a), physi-sorption in cryo-adsorbents (Ahluwalia and Peng, 2009; Kumar et al. 2011; Bénard and Chahine, 2001), chemical absorption (Galli et al. 2010), etc.

Based on a review of the pros and cons of various methods, compressed energy storage and metal hydride hydrogen storage appear to be reasonable choices for the proposed renewable energy based HMA plant. The maximum hydrogen storage capacity is to be decided based on the ability of the hydrogen based wind energy plant's ability to supply power for 12 hours of continuous operation of the plant without any other power input. Future studies will focus on the actual design of a compressed hydrogen storage system by taking into consideration the range of operating pressures, storage space availability, safety considerations, costs, etc. Raju and Kumar (2011a) and Raju and Kumar (2011b) have conducted an excellent in-depth analysis of the hydrogen storage system for automobile application to come up with a good estimate for the weight and volume capacity of the full system. Similar studies are proposed to be conducted in the future but from the point of view of the HMA plant application.

4. Summary and Conclusions

According to some estimates, the production of Hot-Mix Asphalt (HMA) consumes 237,000 BTU/t (275 MJ/t) energy and produces 44 lb CO_2/t (22 kg CO_2/t) (Chehovits and Galehouse, 2010; Zapata and Gambatese, 2005). With the recent push towards sustainable, low-energy, low-emissions and environmentally friendly pavement construction methods, recent studies are focusing on low-temperature asphalt technologies such as Warm-Mix Asphalt (WMA) that have reduced production energy requirements apart from other benefits. Ongoing efforts are also focusing on development and implementation of energy saving guidelines targeting changes in aggregate storage and drying processes, and asphalt plant combustion efficiencies for optimized fuel usage.

This paper proposed a novel application of hydrogen storage based wind energy as a renewable source of energy for operating an existing or new asphalt plant facility. In the proposed innovation, a wind turbine will be installed on site at the HMA plant which will harness energy from the blowing wind. The goal is to use the power generated from the wind turbine to meet the load demand of all components (or at least the major energy consumers) of the HMA plant. Excess wind power will be diverted to the electrolyzer to generate hydrogen which can be stored using different options, the most feasible ones being compressed energy storage and metal hydride hydrogen storage. A hydrogen storage based wind energy plant constructed on site will house the hydrogen storage tanks. Through the use of hydrogen-based energy, the primary sources of greenhouse gas emissions from the HMA plant can be significantly cut down and the resulting cost savings can be enormous. The same technology can be employed in the production of low-temperature asphalt mixes, such as WMA, which can yield even greater environmental and economic benefits. Future research will focus on the actual design of a hydrogen storage system by taking into consideration the range of operating pressures, storage space availability, safety considerations, costs, etc.

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KORIŠĆENJE VODONIKA IZ OBNOVLJIVIH IZVORA ENERGIJE ZA NAPAJANJE BAZE ASFALTNIH MEŠAVINA PROIZVEDENIH VRUĆIM POSTUPKOM

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Sažetak: Značajan deo puteva i autoputeva asfaltiran je asfaltnim mešavinama koje su proizvedene vrućim postupkom. Studije procene životnog ciklusa u odnosu na okolinu pokazale su da se u proizvodnji asfaltnih mešavina vrućim postupkom većina energije troši tokom mešanja asfalta i sušenja agregata, više nego što bude utrošeno prilikom vađenja sirove nafte i destilacije bitumena. Trenutno, prirodni gas je primarni izvor fosilnih goriva i koristi se u proizvodnji 70 – 90% asfaltnih mešavina po vrućem postupku u Sjedinjenim Američkim Državama, dok se ostatak asfaltnih mešavina proizvedenih vrućim postupkom dobija iz nafte, propana, otpadnih ulja i drugih vrsta goriva. Emisija CO_2, oslobođenog prilikom korišćenja fosilnih goriva u različitim industrijskim i transportnim sektorima predstavlja značajan deo emisije štetnih gasova nastalih usled ljudskih aktivnosti. Ova studija ispituje tehničku izvodljivost korišćenja hibridnog sistema energije vetra, kao izvora čiste energije za funkcionisanje čitavog postrojenja za proizvodnju asfaltnih mešavina po vrućem postupku. Imajući u vidu da vetar ne duva uvek istom jačinom, višak energije vetra bi se čuvao u obliku vodonika, koji se smatra lakim, kompaktnim energentom, pogodnim za kasnije korišćenje, čime bi se stvarao stalni izvor električne energije u postrojenjima za proizvodnju asfaltnih mešavina po vrućem postupku, koji bi bio korišćen u slučaju da nema vetra ili da postoji povećana potreba za električnom energijom.

Ključne reči: asfaltna mešavina proizvedena vrućim postupkom, obnovljivi izvori energije, emisija gasova sa efektom staklene bašte, vodonik, vetar.