CHEMICAL ENGINEERING TRANSACTIONS

VOL. 52, 2016

A publication of AIDIC
The Italian Association of Chemical Engineering
Online at www.aidic.it/cet

Guest Editors: Petar Sabev Varbanov, Peng-Yen Liew, Jun-Yow Yong, Jiří Jaromír Klemeš, Hon Loong Lam

ISBN 978-88-95608-42-6; **ISSN** 2283-9216

DOI: 10.3303/CET1652115

Sustainable Production of Asphalt using Biomass as Primary Process Fuel

Fabian Bühler*, Tuong-Van Nguyen, Brian Elmegaard
Technical University of Denmark, Dep. of Mechanical Engineering, Nils Koppels Allé, 2800 Kgs. Lyngby, Denmark

fabuhl@mek.dtu.dk

The production of construction materials is very energy intensive and requires large quantities of fossil fuels. Asphalt is the major road paving material in Europe and is being produced primarily in stationary batch mix asphalt factories. The production process requiring the most energy is the heating and drying of aggregate, where natural gas, fuel oil or LPG is burned in a direct-fired rotary dryer. Replacing this energy source with a more sustainable one presents several technical and economic challenges, as high temperatures, short start-up times and seasonal production variations are required. This paper analyses different pathways for the use of biomass feedstock as a primary process fuel. The analysed cases consider the gasification of straw and wood chips and the direct combustion of wood pellets. The additional use of syngas from the gasifier for the production of heat or combined heat and power is further evaluated during hours without asphalt production. The challenges of having varying seasonal production can be solved by this integration of the production unit to the utility system. The results show the economic and technical feasibility of using biomass for process heating in the asphalt factory. The dryer demand of 6.4 MW can be covered with a biomass input between 7.1 and 8.6 MW. District heat can be produced at competitive prices below 40 € per MWh.

1. Introduction

Asphalt is the major road paving material in Europe and its production is mainly based on fossil fuels (EAPA, 2007). The possibilities of reducing the fossil energy use have been investigated for many years and the industry has approached this topic from different perspectives. A first one is to optimise the design and operation of the asphalt factories. Another is to develop new additives and mixtures for asphalt, which allow lower production temperatures, while keeping the quality constant. However, asphalt factories still use a great amount of fossil fuels, in particular fuel oil, natural gas and LPG, within the drum dryers, to dry and heat the aggregate before it is mixed with bitumen. New asphalt types are not always accepted by customers, because of uncertainties in the long-term performance. This paper investigates the possibilities of supplying the process fuel for the production of hot-mix asphalt from renewable sources. The focus is on biomass systems, comparing different feedstock and technologies, and on their integration within the utility system.

Research has focused on the modelling and optimisation of the rotary dryer of the asphalt plants. Peinado et al. (2011) conducted an energy and exergy analysis, while Le Guen et al. (2013) analysed the heat transfer. The energy efficiencies of the stone and asphalt industry are reviewed by Moray et al. (2006). Possible energy efficiency measures are presented in technical reports by Young (2008) and Stotko (2011). An example of new mixtures is Low-Energy Asphalt (LEA) as presented by Romier et al. (2006). Most relevant to the concept of the current work is a study where the use of hydrogen, originating from wind power, in the rotary dryer is investigated (Gopalakrishnan and Khaitan, 2012). Biomass feedstock (McKendry, 2002a) and conversion technologies (McKendry, 2002b) are described in detail in the literature, but articles analysing case studies for the direct integration of biomass resources for the process industry are rare. Most relevant to the current work are the case studies of biomass cogeneration systems for the steelmaking process (Oliveira et al., 2015) and animal feed production in Brazil (Rodrigues et al., 2013).

The aim of the current work is to assess the economic and technical feasibility, as well as sustainability, of using biomass as a primary process fuel for the asphalt production and integrating the system with the utility.

Please cite this article as: Bühler F., Nguyen T.-V., Elmegaard B., 2016, Sustainable production of asphalt using biomass as primary process fuel, Chemical Engineering Transactions, 52, 685-690 DOI:10.3303/CET1652115

Based on an energy analysis of a hot-mix-asphalt production in a batch mix asphalt factory, which represents the majority of factories in Europe, the potentials and feasibility of utilising biomass as an energy source are investigated. The focus of the analysis is on the direct-fired rotary dryer of the plant, which is the most energy intensive process on-site. The integration of gasification and combustion processes (gasifier and burner), together with a comparison of different feedstock (wood chips, wood pellets, straw), is investigated. The asphalt factory produces in batches: it has short start-up times and is not in operation during cold weather. The options to produce (i) district heat and (ii) combined heat and power are further investigated for gasifiers. The analysed pathways for the current and future biomass scenarios are visualised in Figure 1. For each of the resulting five cases an economic and thermodynamic analysis is performed to find the best solution.

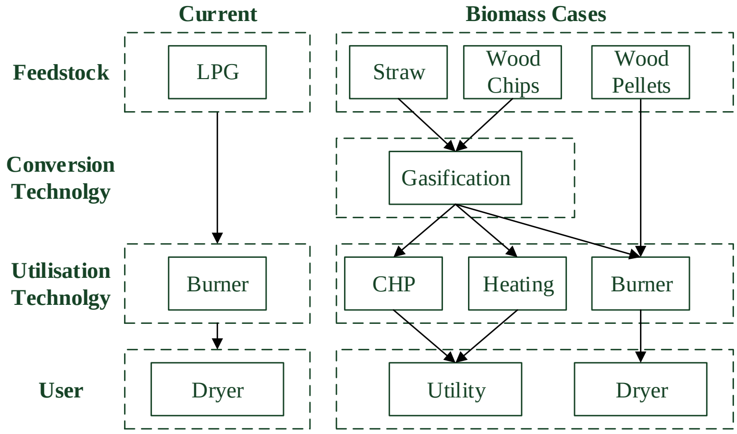

Figure 1: Process pathways of the current system and the analysed biomass cases.

2. Methods

2.1 System Description and Modelling

The system is based on factory data from Denmark, which can be seen as representative for batch-mix asphalt factories in Northern Europe. The reference factory requires 309 MJ of energy per ton asphalt produced, of which 283 MJ are Liquefied Petroleum Gas (LPG) used for the direct-fired rotary dryer. The remaining fuels are used for machinery and room heating, as well as 15.8 MJ/ton electric energy for processes and the heating of bitumen. The values determined are higher than the best available technology, which require less than 250 MJ per ton asphalt.

During nominal operation, the dryer processes aggregate in the form of pebble at a rate of 26 kg/s. The aggregate is heated from the ambient conditions to approximately 200 °C and the moisture content is reduced from approximately 2.65 % to less than 0.03 %. For an asphalt mixture, without reclaimed asphalt, the heat input is about 225 MJ per ton asphalt, based on theoretical calculations and measured data. This corresponds to a heat supply of 6,300 kW in the LPG burner for the present case. The values used in this work reflect the average operation conditions. The heating demand will vary with the moisture content of the raw materials and the production of different mixtures, which use different sized aggregates and reclaimed materials.

The production hours are influenced by weather conditions and infrastructure projects near the factory. In this work, four seasonal weekly profiles are used to approximate the production of the factory during the year. In summer, an average operation of 10 hours per day is used in contrary to winter, where an average operation only occurs for 2 hours each day and in spring/autumn 5 hours a day. This results in an annual asphalt production of 188,000 tons with a consumption of 154,000 tons aggregate.

2.2 Biomass Conversion

The process models of the gasification, combustion, and drying processes are developed in Aspen Plus version 7.2 using the cubic equation of state Redlich-Kwong with Soave modifications and Boston-Mathias adjustments. This thermodynamic property model is widely used to model biomass conversion processes such as gasification, as seen with e.g. the works of Bridgwater (1994) and of Klaas (2015). The compositions of the three types of biomass investigated in this work are presented in Table 1. The ultimate analysis of straw gives a composition (dry basis) of 46.7 %C, 5.73 %H, 42.8 %O, 0.68 %N, for wood chips: 0.15 %S, 79.7 %C, 5.8 %H, 43.2 %O, 0.3 %N, 0.05 %S and wood pellets: 51.4 %C, 5.6 %H, 42.5 %O, 0.08 %N and 0.01 %S.

A complete block diagram, including all the processes considered in the work, is given in Figure 2. The main process pathway includes the gasification step, as well as heat recovery and syngas purification. Three options are then compared: (i) the direct drying of the aggregates, (ii) the `heat mode', in which the maximum district heating production is reached, and (iii) the `CHP mode', in which heat and electricity are produced by using a gas engine and a heat recovery system. The system configuration also includes an additional district heating exchanger prior to the water cleaning step, in the case where the wet syngas from the gasifier has a temperature high enough after air and steam preheating. The system operates in either one of the three modes.

Table 1: Composition of the straw and wood chips given on a proximate and ultimate analysis.

	Straw	Wood chips	Wood Pellets
Proximate analysis [wt%]			
Moisture	14	40	8.7
Ash (dry basis)	4.5	1	0.46
Volatile (dry basis)	70	70	74
Fixed matter (dry basis)	25.5	29	25.54
Energy content [MJ/kg]			
Higher heating value	16.4	11.3	18.2
Lower heating value	14.9	9.5	16.8
Economic Parameters			
Price [€/GJ_{LHV}]	5.5	6.1	8.3
Annual Price Increase [%]	0.72	0.72	0.33

The gasifier was developed under the assumption of steady-state operation and neglecting heat losses and pressure drops. The gasifier is considered operating under atmospheric pressure for which the following process parameters were assumed:

- tar formation is not considered, fuel-bound nitrogen is converted to NH3 and fuel-bound sulphur to H2S, while chlorine, silicium and other chemical compounds typically present in biomasses with a content smaller than 1 % in mass are neglected;
- char is assumed as pure carbon;
- drying is performed prior to the gasification internally in the two-stage gasifier, and the removed water is used as gasifying agent together with air;
- drying takes place at 300 °C, devolatilization at 600 °C and gasification at 800 °C;
- the gasifying agents in the gasification process are air and steam, which are preheated to 150 °C, an excess ratio of 20 % is considered for air, and the steam-to-air ratio is 0.35;
- reaction kinetics (e.g. water-gas-shift) are not considered and the reactions are assumed to attain equilibrium at each stage (e.g. devolatilization, gasification, combustion);
- the exhaust gases resulting from the char combustion are at 165 °C to ensure enough driving heat transfer force in the air and steam preheating steps;
- gas cleaning is assumed ideal with full removal of the sulphur compounds and water removal takes place at 50 °C, the heat recovered in this process may be used for district heating purposes, but not for asphalt drying (as this takes place in a single component);

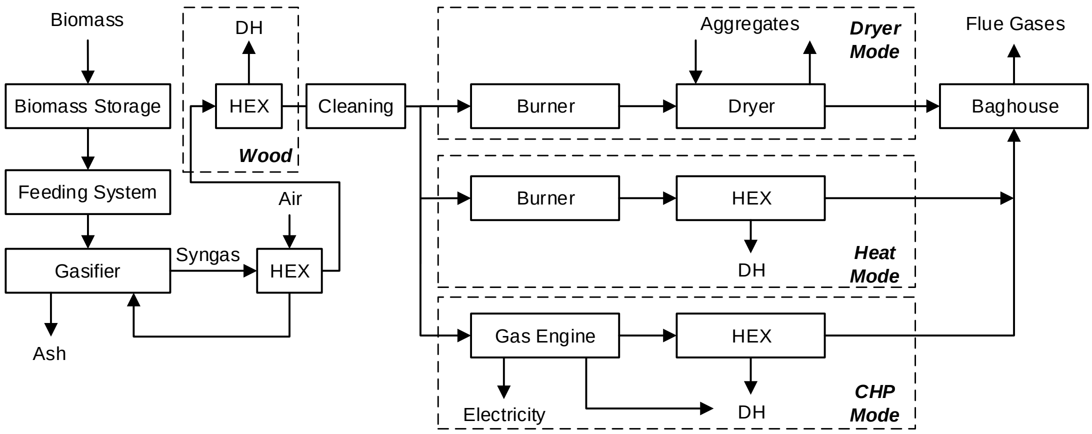

Figure 2: Block diagram of the gasification process layouts investigated (drying, heat and CHP modes).

The produced syngas is combusted at 1,200 °C in the burner and the exhausts from the aggregate dryer are rejected at 71 °C for drying asphalt. For the production of heat and power in the gas engine, a pressure ratio of 11 was assumed and using a maximum combustion temperature of 1,400 °C, a polytropic efficiency of 85

% and an isentropic efficiency of 80 % for the compressors and turbines, respectively. The district heating water is has a supply and return temperature of 90 °C and 50 °C.

2.3 Economic and Sustainability

To determine the economic feasibility of powering the asphalt factory with biomass, the investment and operating costs of the solutions are found and compared to the existing system. The techno-economic comparison is based on the Net Present Value (NPV) and Payback Period (PBP) of the new systems (Pintarič & Kravanja, 2015). The evaluation is done over a 20 year period, using a discount rate of 5 % and an inflation rate of 2 %. For the integration with the utility system, time-of-day tariffs for local CHP units in Denmark are used (Energinet.dk, 2013). The unit price for electricity varies from 31.2 to 87.3 €/MWh depending on the season, day and time. This price is expected to increase with 3.6 % per year (Energinet.dk, 2014). The unit price, which can be obtained for district heating, depends also on local regulations. Therefore two cases are considered: (i) a unit price of 30 € per MWh is considered which would be paid by the local utility operator and (ii) the unit price for heating is found as the annuities divided by the annual heat production. The costs of biomass are based on a market analysis and price forecasts for Denmark (Bang et al., 2013). The prices for biomass found in Table 1 include costs for transport and all taxes payable in Denmark, where biomass is currently exempted from the energy and CO_2 tax. For LPG, the price is 16 € per GJ fuel and is expected to increase by 2.3 % per year.

The investment costs for the main equipment to be purchased, as well as its O&M costs are estimated based on case studies by Obernberger and Thek (2008) and the technology catalogue of the Danish Energy Agency (2015). The investment costs consist, where applicable, of gasifier, district heating boiler and gas engine. Equipment connected directly with the operation, such as flue gas cleaning and fuel storage are included in the costs. The utility system is supplied by the new biomass system during 6,000 hours a year. This results together with the asphalt production in 7,880 annual operating hours.

Table 2: Investment costs for the main equipment and O&M Costs for the different cases.

	Wood Chip CHP	Wood Chip Heat	Straw CHP	Straw Heat	Wood Pellet Burner
Gasifier [M€]	5.34	5.34	5.68	5.68	-
Gas Engine [M€]	1.45	-	1.72	-	-
Boiler/ Burner [M€]	-	0.75	-	0.85	2.8
O&M [€/GJ_{LHV}]	1.7	1.2	1.7	1.2	0.3

To assess the sustainability in a first approach the Global Warming Potential over 100 years (GWP100a) is used to compare the different systems. The analysis is based on data from the Ecoinvent database for Switzerland, considering the fuel at the factory. The GWP100a is allocated to the production of asphalt, heat and power and compared to the production with LPG and emissions of heat and power from CHP in Denmark. All values refer to a life cycle approach. For heat and power, the emissions are allocated based on the products exergy content. With the given district heat temperatures, 83 % of the total emissions are allocated to electricity.

3. Results and discussion

3.1 Biomass Integration

The current system for the production of hot mix asphalt uses in the nominal production state 266.8 MJ LPG per ton per ton of aggregate processed. This corresponds to a fuel input to the dryer of 6.4 MW.

Table 3: Results for the gasification solutions for a constant biomass flow rate

Conversion	Biomass	Mode	Case	Drying [MW]	Heat [MW]	Power [MW]	Flow Rate [kg/s]
Gasification	Straw	Asphalt	-	6,400	-	-	0.58
Gasification	Straw	Heat	ST-H	-	6,240	-	0.58
Gasification	Straw	CHP	ST-CHP	-	3,550	1,950	0.58
Gasification	Wood Chips	Asphalt	-	6,400	890	-	0.84
Gasification	Wood Chips	Heat	WC-H	-	7,040	-	0.84
Gasification	Wood Chips	CHP	WC-CHP	-	4,450	1,500	0.84
Combustion	Wood Pellets	Asphalt	WP	6400	-	-	0.42

In Table 3 the results for the gasification and combustion of biomass are shown which should cover the heat demand for drying. The cooling of syngas, necessary to reduce its vapour content, provides some excess heat in the case of wood chips, which can be utilised for district heating (Figure 2). The lowest flow rate is obtained for wood pellets, as the fuel has a high heating value and is directly combusted in the dryer. The burner at the dryer can operate with particles and tar in the syngas and the asphalt may contain some of the particles. A clean producer gas is however required for the gas engine increasing the system complexity, also compared to the heat only mode. In case of CHP production, the production plant of the asphalt factory allows the operation of the gas engine during 55 % of the hours with high electricity demand.

3.2 Economic Evaluation

The economic analysis shows that the use of wood chip gasification systems in combination with a district heating unit is the most profitable option with a NPV of 4.6 million Euro. Despite the higher fuel costs for wood chips, the higher fuel efficiency for the conversion of wood chips results in the highest NPV and a low PBP. For the generation of combined heat and power, the use of a straw gasifier has the second highest NPV. The straw CHP system produces the largest amounts of electricity, which has a high value in the future due to the forecasted increase in electricity costs. The feasibility of this solution is thus more sensitive to changes in electricity price compared to wood chips as can be seen in Figure 1.

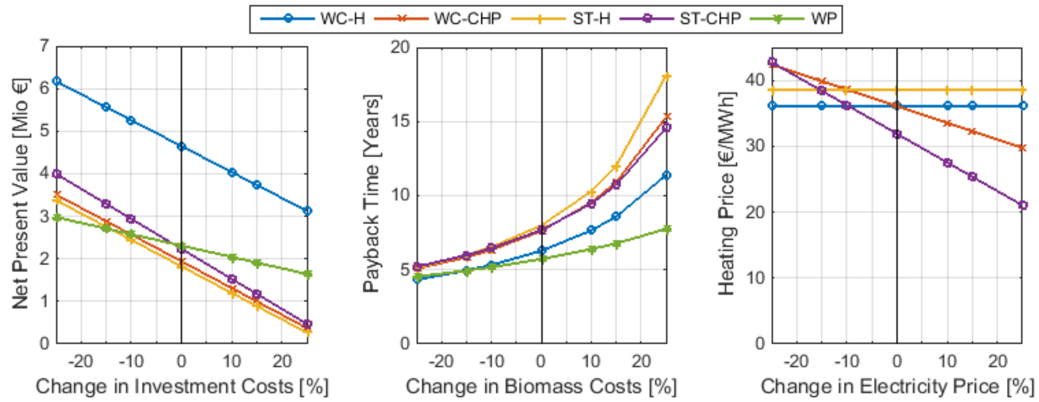

Figure 1: Results of the economic analysis showing the net present value, payback time and heating price. The sensitivity of the results for changes of investment costs, biomass costs and electricity price is further displayed.

The NPV and PBP, based on a fixed heating price show that the investment is profitable and has acceptable payback times for all pathways. Uncertainties in the investment can however influence the outcome, but the wood chip heating system remains to be the preferred one. Due to current legislation, the construction of a heat only plant with biomass might not be possible. The heating price with the biomass CHP plant is competitive with other technologies. For the asphalt production, the switch to biomass gasification causes annual fuel savings of approximately 700,000 €. The use of wood pellets as process fuel leads to annual fuel savings of 600,000€.

3.3 Sustainability Evaluation

The global warming potential of emissions occurring during the production of asphalt can be greatly reduced by using biomass instead of fossil fuels as shown in Table 4. With wood chips and straw, the emissions are around 90 % lower than the ones of LPG and with wood pellets they can still be reduced by almost 80 %. The emissions for wood pellets are higher as they have to be dried and pressed, and are often imported from abroad. When only producing heat with the biomass system, the GWP is less than the one found in current production of district heat in CHP plants in Denmark. The GWP per unit of electricity can be reduced by up to 80 % when using a wood chip gasifier with a gas engine. A more detailed analysis of the biomass transport for Denmark is however necessary to obtain fully comparable GWP 100a indicators for the different biomass types.

Table 4: Global Warming Potential over 100 (GWP100a) for the production in the base and biomass cases, only considering aggregate drying process.

		Base	WC -H	WC-CHP	ST- H	ST- CHP	WP
Asphalt	[kgCO2eq/t]	16.7	1.3	1.3	1.9	1.9	3.6
Electricity	[kgCO2eq/MWh]	371.6	-	72,0	-	81.3	-
District Heat	[kgCO2eq/MWh]	77.9	17.9	4.8	30.7	9.3	-

4. Conclusion

This paper investigates the use of biomass as a process fuel for the asphalt production in combination with the production of heat and power. Asphalt factories have short start up times and variations in seasonal production, which makes the integration of the factories energy supply with the utility interesting. Syngas from a biomass gasifier can be used in the asphalt plants direct-fired rotary dryer and during hours with no production in a gas engine or district heating boiler. The model of the gasifier, covering a heating load of 6.4 MW for the dryer resulted in a production of up to 1.95 MW_{el} with straw and up to 7 MW_{th} with wood chips in the heat only case.

From an economic view, a wood chip gasifier with the production of district heat yields the highest net present value. The lowest district heating price is obtained with straw gasification and combined heat and power production. All solutions have a payback time of less than 10 years for the investment and are subject to uncertainties discussed in a sensitivity analysis. At the end, a sustainability assessment is conducted based on the global warming potential over 100 years of the fuels used in the different systems. The specific emissions for the drying of aggregate can be reduced from 16.7 kg of CO_2 equivalent per ton of product to less than 2 kg of CO_2 equivalent per ton of product. In addition, the produced heat and power have lower specific emissions than the average ones in Denmark. Overall an integration of a biomass system into a stationary asphalt plant is economical and technical feasible, while reducing the CO_2 emissions.

Reference

Bang C., Vitina A., Sterling J., Lindboe H., 2013, Analysis of biomass prices, Ea Energyanlysis A/S, Copenhagen.

Bridgwater A.V., 1994, Advances in thermochemical biomass conversion, Vol. 1-2, Blackie Academic and Professional.

Danish Energy Agency, 2015, Technology Data for Energy Plants - Generation of Electricity and District Heating, Energy Storage and Energy Carrier Generation and Conversion.

EAPA (European Asphalt Pavement Association), 2007, Environmental Guidelines on Best Available Techniques (BAT) for the Production of Asphalt Paving Mixes, Brussels, Belgium.

Energinet.dk, 2014, Energinet.dk's analyseforudsætninger 2014-2035 <www.energinet.dk> accessed 29.02.2016 (in Danish)

Energinet.dk, 2013, Time-of-day tariff for local CHP units <www.energinet.dk> accessed 29.2.2016

Gopalakrishnan K., Khaitan S., 2012, Use of Hydrogen from Renewable Energy Source for Powering Hot-Mix Asphalt Plant, International Journal for Traffic and Transport Engineering, 2(1), 30–43.

Le Guen L., Huchet F., Dumoulin J., Baudru Y., Tamagny P., 2013, Convective heat transfer analysis in aggregates rotary drum reactor, Applied Thermal Engineering, 54(1), 131–139.

Klaas M., 2015, Fuels From Biomass: An Interdisciplinary Approach: A collection of papers presented at the Winter School 2011 of the North Rhine Westphalia Research School "Fuel production based on renewable resources" associated with the Cluster of Excellence "Tailor-M, Springer Berlin Heidelberg.

McKendry P., 2002a, Energy production from biomass (part 1): Overview of biomass, Bioresource Technology, 83(1), 37–46.

Mckendry P., 2002b, Energy production from biomass (part 2): conversion technologies. Bioresource Technology, 83(1), 47–54.

Moray S., Throop N., Seryak J., Schmidt C., Fisher C., Antonio M., 2006, Energy Efficiency Opportunities in the Stone and Asphalt Industry Overview of the Stone Crushing Industry Stone Crushing Process Overview, In Proceedings of the Twenty-Eighth Industrial Energy Technology Conference, New Orleans.

Obernberger I.,Thek G., 2008, Cost assessment of selected decentralised CHP applications based on biomass, In 16th European Biomass Conference & Exhibition, 1–11.

Oliveira T., Assis P., Leal E., Ilídio J., 2015, Study of biomass applied to a cogeneration system: A steelmaking industry case, Applied Thermal Engineering, 80, 269–278.

Peinado D., de Vega M., García-Hernando N., Marugán-Cruz C., 2011, Energy and exergy analysis in an asphalt plant's rotary dryer, Applied Thermal Engineering, 31(6-7), 1039–1049.

Pintarič Z.N., Kravanja Z., 2015, The importance of using discounted cash flow methodology in techno-economic analyses of energy and chemical production plants, In Proceedings of the 10th Conference on Sustainable Development of Energy, Water and Environment Systems, 1–14.

Rodrigues M., Arrieta F., Sodré J., 2013, Small scale biomass CHP plant: An assessment for an animal feed industry, Applied Thermal Engineering, 59(1-2), 174–181.

Romier A., Audeon M., David J., Martineau Y., Olard F., 2006, Low-Energy Asphalt with Performance of Hot-Mix Asphalt, Transportation Research Record, 1962(1), 101–112.

Stotko O., 2011, Energy and Related Carbon Emission Reduction Technologies for Hot Mix Asphalt Plants, In 10th Conference on Asphalt Pavements for Southern Africa - CAPSA, 1–9.

Young T.J., 2008, Energy Conservation at the Plant Makes Sense and Saves Dollars, Hot Mix Asphalt Technology, 28–39.