Research into the use of a lean burn and a stoichiometric heavy duty engine fuelled with a blend of hydrogen and natural gas

L. De Simio, M. Gambino & S. Iannaccone
Istituto Motori, Italian National Research Council, Napoli, Italy

Abstract

Energy sustainability implies the increase of share of renewable sources, as well as the reduction of inefficiencies during generation and distribution. However, a large use of renewable intermittent energy sources, such as solar and wind, in power plants and in small generators distributed could complicate the electrical grid. An important aspect of the impact of electrical networks operating on the distribution system concerns the regulation of voltage. In the case of surplus of electricity decentralized production, energy storage could be a viable solution. In this scenario the production of hydrogen by electrolysis as energy carrier, with oxygen as a byproduct, can become appealing. Hydrogen in urban areas could easily be used in blends with natural gas in urban vehicle fleets. This solution is flexible regarding the amount of hydrogen available and in any case natural gas is the best choice for the internal combustion engine for urban fleets. The use of natural gas in stoichiometric or lean burn engines guarantees a very low level of toxic emissions and zero particulate matter without the need of a trap, even after the vehicle has accumulated a considerable mileage. In particular, only the NOx emissions are harmful, since the emission of hydrocarbons are mainly composed of methane, which is not toxic to human health. In this paper the effect of the addition of hydrogen to natural gas, in the amount of 15% by volume, on the emission of a stoichiometric and a lean burn heavy duty engine was studied. The tests were carried out on the European transient cycle. The results show that with the stoichiometric engine no special attention must be put in the supply change while with the lean burn engine the problem of poor NOx control suggests adjusting the calibration of ignition; with the aim of not compromising the engine emission.

Keywords: hydrogen, hydromethane, natural gas, ETC, sustainability.

WIT Transactions on Ecology and The Environment, Vol 162, © 2012 WIT Press
www.witpress.com, ISSN 1743-3541 (on-line)
doi:10.2495/EID120261

1 Introduction

The evolution of the electricity grid is a key challenge in Europe to enable the development of renewables sources. In fact, solar and wind energy are abundant and distributed, but are also intermittent and characterized by a poor ability to control and predict the amount of electricity that can be produced. Distributed generation also implies that the grid should become bidirectional. Therefore, the distribution network will switch from a passive to an active role [1–3], changing the way in which electricity is produced, transmitted and consumed. An important aspect of the impact of electrical networks operating on the distribution system concerns the regulation of voltage. The fluctuating nature of renewable energy will require storage systems or demand management while the distribution of generation points will involve node voltage control. In this scenario also a flexible coproduction of hydrogen (H_2) as energy carrier could be a viable solution [4–8]. The electricity network should manage in an intelligent way different energy vectors, distributed power generators and dispersed energy storage devices, instead of the electricity alone [9].

Hydrogen in urban areas could be easily used in blends with natural gas in an urban bus natural gas fleet. This solution is flexible regarding the amount of hydrogen available. Compressed Natural Gas (CNG) has proved to be a concrete alternative to gasoline and diesel fuels for vehicle propulsion. Natural gas is a clean fuel since toxic compounds like sulphur, or potential toxic, like benzene and higher molecular weight hydrocarbons, or highly reactive such as olefins, are absent. Nowadays, most CNG engines operate in spark ignition (SI) mode, for both light and heavy-duty application. Particularly in this latter case the typical disadvantages of a CNG fuel tank weight and allocation are overcome because of the wide space availability and the small relative increase in weight. Moreover in the case of public transportation in urban areas, the route is scheduled and therefore the NG option can be chosen according to the autonomy range. The utilization of pure hydrogen, in substitution of CNG, in a spark ignition engine, drastically reduces vehicle operating range (by about 70% compared to methane, CH_4) due to its lower energy density by volume. Furthermore, H_2 has a low ignition energy in air (0.02 mJ versus 0.29 of CH_4, at stoichiometric conditions [10]), which ensures the combustion even with very lean mixtures but makes it subject to pre-ignition phenomena by contact with hot spots or residual gas. The pre-ignition, unlike the knocking, cannot only be controlled with the ignition timing, but requires substantial modifications to the engine. The use of methane-hydrogen mixtures containing H_2 between 10 and 30% by volume offers instead the opportunity to exploit the positive aspects related to hydrogen without substantial modification of already existing natural gas engines, avoiding the drawbacks of the use of pure hydrogen.

Bibliographic data highlight a flame front speed propagation increasing when H_2 is added to NG [11, 12]. At the same time, a reduction of carbon monoxide (CO) and unburned hydrocarbons (THC) occurs, with benefits on thermodynamic efficiency. On the contrary, nitrogen oxide (NOx) emissions could be higher for more elevated temperatures at stoichiometric conditions [13]. Hydrogen added to natural gas gives us the possibility to expand the lean burn limit [14–16], due to a more stable combustion [17]. A more stable combustion permits us to use higher exhaust gas recirculation to optimize the engine [18–20]. A review of H_2 use in internal combustion engine is given in [21]. As hydrogen is a carbon-free fuel, the reduction in carbon dioxide (CO_2) emissions is a direct function of H_2 content in the blend, at the same engine efficiency. For blends containing a 30% in volume of H_2, more than 10% CO_2 reduction is expected. In any case the way of hydrogen production represents a crucial aspect.

In this paper two heavy duty engines for urban bus application, a stoichiometric and a lean burn, were tested on the European transient test (ETC) cycle. The engines were fuelled with NG and with a blend of NG and 15% by volume of H_2. The effect on engine exhaust emission was examined.

2 Experimental setup

The experimental activity was carried out on two commercial SI heavy duty engines. A 200 kW stoichiometric engine (Table 1 and Figure 1) equipped with a three way catalyst (TWC) and an oxygen lambda sensor and a 170 kW lean burn engine (Table 2 and Figure 2) equipped with an oxidation catalyst.

Table 1: Stoichiometric SI heavy duty engine main characteristics.

Turbocharged intercooler 6-cylinder in line	
Total displacement	7800 cm3
Bore x stroke	115 x 125 mm
Compression ratio	11:1
Rated power	200 kW @ 2100 rpm
Rated torque	1100 Nm @ 1100÷1650 rpm
Boost pressure	180 kPa, with waste gate valve
Intercooler	Air to water (external line)
NG feeding system	Electronic timed multi-point injection
Power Density	25.6 kW/dm3

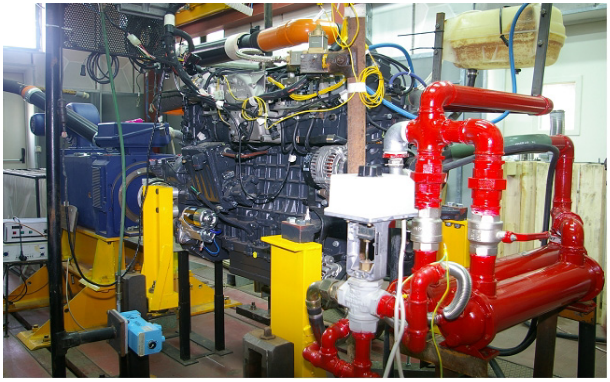


Figure 1: Stoichiometric heavy duty NG engine at dynamic test bed.

Table 2: Lean burn SI heavy duty engine main characteristics.

Turbocharged intercooler 6-cylinder in line	
Total displacement	6883 cm3
Bore x stroke	106 x 130 mm
Compression ratio	10.5:1
Rated power	170 kW @ 2200 rpm
Rated torque	810 Nm @ 1200÷1800 rpm
Boost pressure	124 kPa @ 2200 rpm
Intercooler	Air to Air
NG feeding system	Electronic timed multi-point injection
Power Density	24.7 kW/dm3

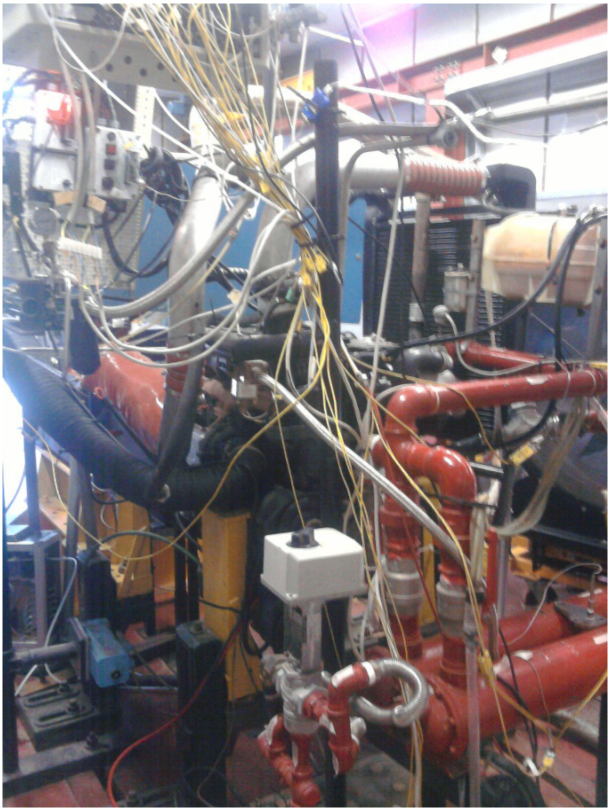


Figure 2: Lean burn heavy duty NG engine at dynamic test bed.

The engines were fuelled with NG and with a blend of pure methane and 15% of H_2 by volume also named "hydromethane" (HCNG). The characteristics of the fuels used in the tests are reported in Table 3. The NG used has 85% of methane content while the rest is principally constituted of ethane and inert gases. The HCNG, represents instead an enriched NG in which substances different from methane were replaced by hydrogen.

Table 3: Characteristics of tested fuels.

	CH_4 % vol.	H_2 % mass	SAFR kg/kg	LHV MJ/kg	ρ^* kg/Sm^3	H/C n/m	CO_2 g/MJ
NG	85	0	15.7	45.8	0.83	3.7	57
HCNG	85	2.13	17.3	50.7	0.63	4.3	53

* *Density at 1 bar and 15°C*

The experimental activity was carried out on an AVL Puma 5 dynamic test bed, integrated with an emission test bank, able to control the engine and carry out continuous measurements during the ETC respecting all the constraints imposed by the legislation. The ETC [22], which is the test approval for gaseous SI heavy duty engines, is fixed through a table of normalized values of speed and torque. The full torque curve of the engine is used to denormalize that table. The dynamic test has a duration of 1800 s and can be split in three subsets of 600 s: in the first has very sudden changes of speed and load typical of the operation in urban areas, with continuous phases of “stop and go”. The second subset is related to rural roads with less intensive variations of speed and load, while the last is representative of motorway running. Figure 3 shows the profiles of normalized torque and speed to run during the ETC. More details about the instrumentation used to run the ETC tests are reported in Table 4.

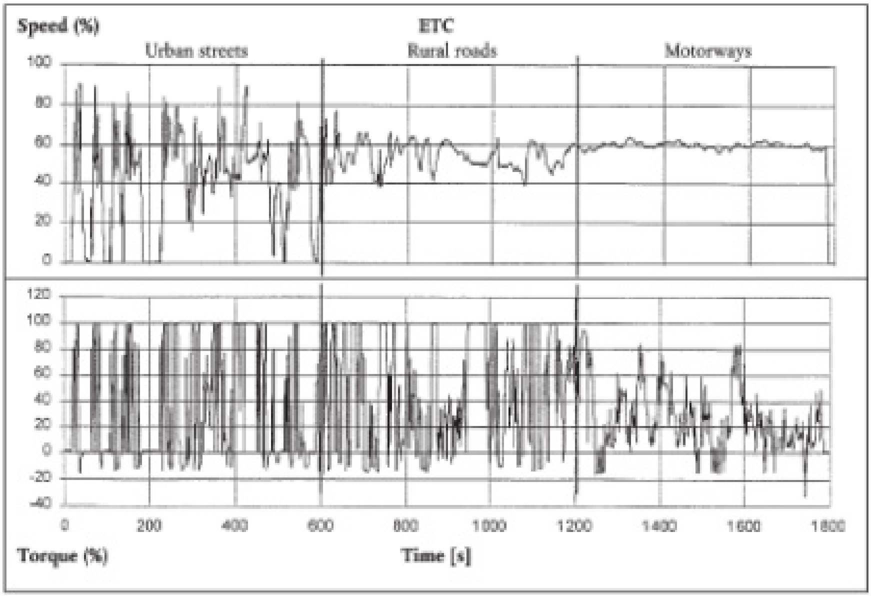
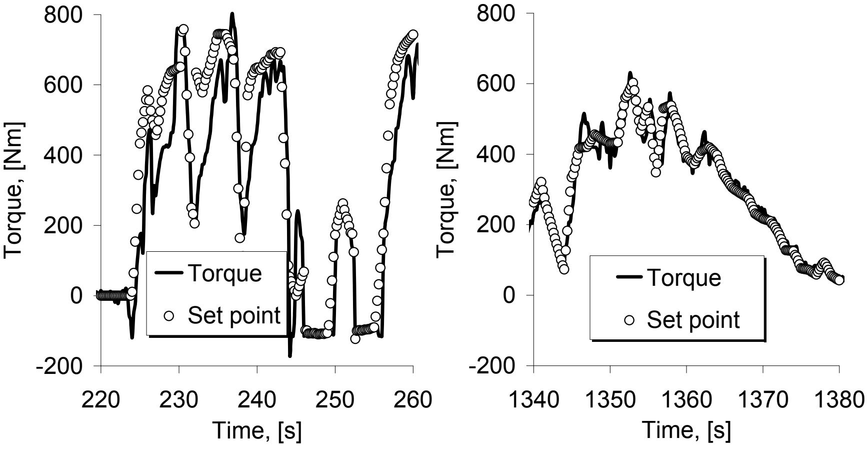


Figure 3: A graphical display of the ETC dynamometer schedule [22].

Table 4: Instrumentation for emission measurement according the ETC test.

Unit	Type	Range	Accuracy
TORQUE	TORQUE FLANGE HBN T 10F	2000 Nm	± 0.2 % of reading
SPEED	AFA AVL DINAMOMETER	3500 rpm	< 0.2 % of reading
FUEL MASS FLOW METER	MICRO MOTION ELITE	50 kg/h	<1 % of reading
AIR MASS FLOW METER	ABB SENSY FLOW P	1200 kg/h	± 1 % of reading
ATMOSPHERIC INTAKE EXHAUST PRESSURE	DRUCK PT X 1400	800–1200 mbar 400 mbar	± 0.1 kPa (± 0.25 %) of range
OTHER PRESSURES	DRUCK PT X 1400	-	± 0.25 % of range
TEMPERATURE	-	-	± 1 % of reading
THC	MULTIFID 14 EGA	0–10000 ppm C_3	0.5% of range
CH4		1–10000 ppm C_1	
CO	URAS 14 EGA	0–10%	< 1 % of range
NO_X	CLD ECOPHYSICS	0–5000	< 1 % of range
NO	CLD 700 REHT PERFORMANCE		
CO_2	URAS 14 EGA	0–20%	1 % of range
O_2	MACROS 16 EGA	0–25%	0.5 % of range
PARTICULATE SAMPLING SYSTEM	CONTROL SYSTEM PSS20	1.5 m^3/h	± 0.2 % of range
PT ELECTRONIC BALANCE	SARTORIUS 4503 MICRO	4.1 g	± 5 ng of reading

The two diagrams of Figure 4 represent two short sections relating to the torque profile of the urban section in the range 220÷260 s of the ETC cycle (*a*) and of the motorway in the range of 1300÷1450 s (*b*). The figure highlights the fact that the engine must operate with considerable variations in performance, which require very fast and accurate control for a correct execution of the cycle.



(a) *(b)*

Figure 4: Torque measured for the lean burn engine compared with the set point of the ETC cycle: *(a)* part of urban phase, *(b)* part of motorway phase.

3 Results

For the stoichiometric engine the comparison between the two test fuels has been carried out without changing the electronic control unit (ECU) calibration. Therefore the same spark advance (SA) map was used for both CNG and HCNG fuelling. For the lean burn engine, instead, the SA map was adjusted. The experimental activity has resulted in establishing a SA reduction of 2.5 crank angle degrees on the whole engine map. In Table 5 the comparison between the results obtained on the ETC test with the two engines and the two tested fuels is reported. Apart from the CH_4 emissions, CO, NMHC, and NOx emissions were within the enhanced environmentally friendly vehicle (EEV) limits in all the cases. The control of CH_4 emission is critical and strongly dependent on the exhaust temperature. Particulate matter (PT) emissions were considerably under the limits, especially for the lean burn engine. Slightly lower energy consumption was obtained with the lean burn engine. Using HCNG a reduction of CO_2 emission due to a higher H/C was obtained.

For the stoichiometric engine the CO emissions are the most critical and this is due to the fact that the ECU sets a slightly rich mixture to permit a high efficiency of NOx reducing to the catalyst. Therefore, changing from CNG to HCNG gives some benefits; in fact the reduction of H/C of the fuel also results in a reduction of CO emissions. Instead, although the NOx emissions increase upstream the catalyst, the high NOx conversion efficiency does not increase NOx emission downstream the catalyst when HCNG is used (Figure 5). NOx emission increasing upstream the catalyst with HCNG is due to a faster combustion at parity of SA. In particular the burning gravity centre (BGC), the

Table 5: Comparison of results of the ETC tests for both the stoichiometric and the lean burn engine with the EEV limits.

	CO	**NMHC**	**CH4**	**NOx**	**PT**	**CO2**	**BSEC**
			g/kWh			g/kWh	MJ/kWh
Stoichiometric 200 kW CNG	2.36	0.07	0.68	0.49	<0.01	714	12.5
Stoichiometric 200 kW HCNG	2.15	0.00	0.67	0.52	<0.01	670	12.7
Lean burn 170 kW CNG	0.00	0.06	2.32	1.37	<0.001	705	12.4
Lean burn 170 kW HCNG	0.00	0.00	2.26	1.64	<0.001	643	12.2
Limits							
EURO III 2000	*5.45*	*0.78*	*1.60*	*5.00*	*0.16*		
EURO IV 2005	*4.00*	*0.55*	*1.10*	*3.50*	*0.03*		
EURO V 2008	*4.00*	*0.55*	*1.10*	*2.00*	*0.03*		
EEV	*3.00*	*0.40*	*0.65*	*2.00*	*0.02*		

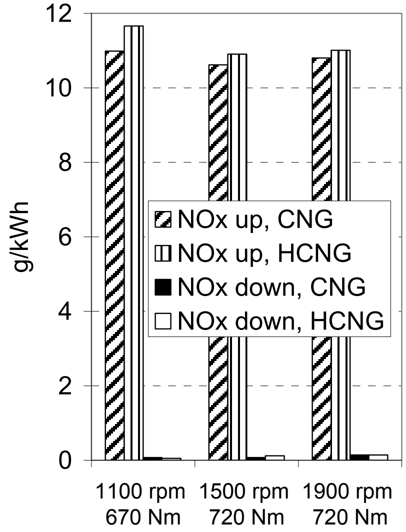


Figure 5: NOx emission upstream and downstream the TWC for the stoichiometric engine with CNG and HCNG at steady state.

crank angle at which 50% of the fuel mass is burned is advanced in the case of HCNG, Figure 6(*b*). The pressure cycles, Figure 6(*a*), have been measured in the combustion chamber of the stoichiometric engine with KISTLER piezoelectric pressure transducers (sensitivity 26 pC/bar). Pressure cycles were measured as mean values of 128 consecutive cycles.

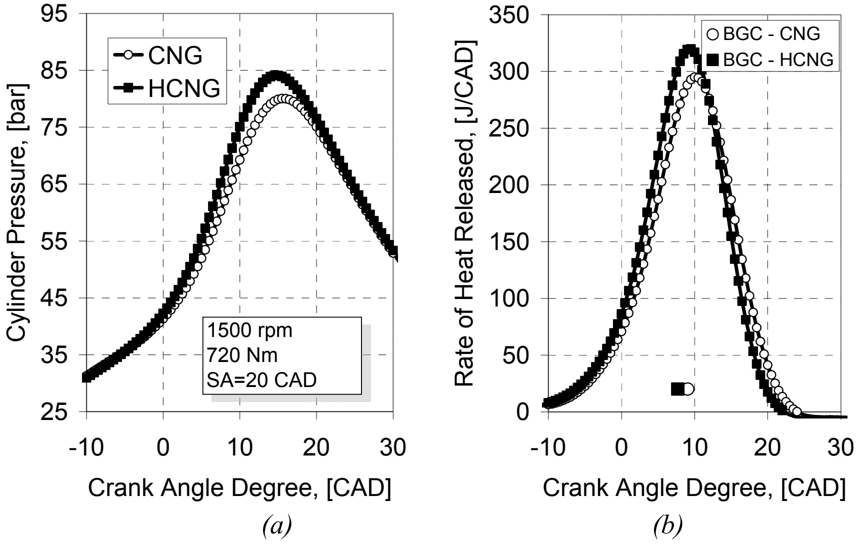


Figure 6: CNG and HCNG cylinder pressure cycles (*a*) and heat release rate curves (*b*) at 1500 rpm and 720 Nm with the same SA calibration.

For the lean burn engine NOx control is possible only in the combustion chamber; a post-reduction system not being present. In addition for this engine the lowest exhaust temperature makes the conversion efficiency of the oxidation catalyst respect to the stoichiometric engine more variable. In Table 6 it is possible to analyze both the two mentioned problems for the lean burn engine. Looking at the first and the second lines, CO and NMHC conversion is almost complete while CH_4 is reduced by about 50%. Considering the standard deviation of results, there is a low variation of engine CH_4 exhaust emission upstream of the catalyst and a high variation downstream of the catalyst. This is due to the efficiency of the conversion system, in particular in the first phase of the ETC cycle. In fact, for this kind of engine also the presence of insulation on the exhaust could influence the CH_4 conversion efficiency of the catalyst. Thus the results on CH_4 obtained could be reduced with a different exhaust system. About NOx emission, from the second and third lines, an increase of more than 80% with HCNG is obtained when the ECU SA calibration is not adjusted. Therefore, in the fourth line, an optimization of the SA calibration was performed to retain the same level of NOx emission of the CNG case.

4 Conclusion

The use of natural gas in stoichiometric or lean burn engine guarantees very low level of toxic emission and zero particulate matter. Hydrocarbon emissions are mainly constituted by methane that is not toxic for human health therefore only NOx emissions are harmful. In this paper the effect of hydrogen addition to

Table 6: Results of the ETC tests for the lean burn engine with different conditions.

	CO		**NMHC**		**CH4**		**NOx**	
	Mean value	Stand. deviat.	Mean value	Stand. deviat.	Mean value	Stand. deviat.	Mean value	Stand. deviat.
	g/kWh	%	g/kWh	%	g/kWh	%	g/kWh	%
Lean burn 170 kW CNG Up. Cat.	2.74	0.7	0.91	4.7	5.16	2.6	1.40	7.1
Lean burn 170 kW CNG Down. Cat.	0.00	0.1	0.06	0.1	2.32	26.9	1.37	6.9
Lean burn 170 kW HCNG Down. Cat.	0.00	0.1	0.00	0.1	2.10	20.1	2.45	8.1
Lean burn 170 kW HCNG SA Optimized Down. Cat.	0.00	0.1	0.00	0.1	2.26	18.3	1.64	7.8

natural gas in the amount of 15% by volume on emission of a stoichiometric and a lean burn engine was studied. The study was carried out on the basis of European transient cycle tests. The results highlight that with a stoichiometric engine no particular attention should be placed when the engine is switched from CNG to HCNG, in fact the NOx increasing is only upstream the three way catalyst. With a lean burn engine ECU SA adjustment should be required when the engine is fuelled with HCNG with the aim of not compromising the very low engine out emissions with NOx increasing.

Nomenclature

CNG	Compressed natural gas
BGC	Burning gravity centre
BSEC	Brake specific energy consumption
CAD	Crank angle degree
CH4	Methane
CO	Carbon monoxide
CO2	Carbon dioxide
ECU	Electronic control unit
EEV	Enhanced environmentally vehicles
ETC	European transient cycle
H2	Hydrogen

HCNG	Hydromethane
LHV	Lower heating value
NMHC	Non methane hydrocarbon
NOx	Nitrogen oxides
PT	Particulate
SA	Spark advance
SAFR	Stoichiometric air fuel ratio
SI	Spark ignition
THC	Total unburned hydrocarbons
TWC	Three way catalyst

References

[1] Battaglini, A., Lilliestam, J., Haas, A., and Patt, A. (2009). Development of SuperSmart Grids for a more efficient utilisation of electricity from renewable sources. *Journal of Cleaner Production*, *17*(10), 911-918.
[2] Hammons, T. (2008). Integrating renewable energy sources into European grids. *International Journal of Electrical Power and Energy Systems*, *30*(8), 462-47.
[3] Crossley, P., and Beviz, A. (2010). Smart energy systems: Transitioning renewables onto the grid. *Renewable Energy Focus*, 11(5), 54-59.
[4] Hemmes, K., Guerrero, J. M., and Zhelev, T. (2011). Highly efficient distributed generation and high-capacity energy storage. *Chemical Engineering and Processing: Process Intensification*, *51*, 18-31.
[5] Fingersh, L.J. (2003). Optimized Hydrogen and Electricity Generation from Wind, NREL/TP-500-34364.
[6] Delucchi, M. a., and Jacobson, M. Z. (2011). Providing all global energy with wind, water, and solar power, Part II: Reliability, system and transmission costs, and policies. *Energy Policy*, *39*(3), 1170-1190.
[7] Kelly, N. A., Gibson, T. L., Cai, M., Spearot, J. A., and Ouwerkerk, D. B. (2010). Development of a renewable hydrogen economy: Optimization of existing technologies. *International Journal of Hydrogen Energy*, *35*(3), 892-899.
[8] Barton, J., and Gammon, R. (2010). The production of hydrogen fuel from renewable sources and its role in grid operations. *Journal of Power Sources*, *195*(24), 8222-8235.
[9] Orecchini, F., and Santiangeli, A. (2011). Beyond smart grids – The need of intelligent energy networks for a higher global efficiency through energy vectors integration. *International Journal of Hydrogen Energy*, *36*(13), 8126-8133.
[10] Chapman, K.S., Patil, A. (2008). "Performance, Efficiency, and Emissions Characterization of Reciprocating Internal Combustion Engines Fuelled with Hydrogen/Natural Gas Blends", Final Technical Report, DOE Award DE-FC26-04NT42234.
[11] Boulouchos K., Dimopoulos P., Hotz R., Rechsteiner C., Soltic P. (2007). "Combustion Characteristics of Hydrogen-Natural Gas Mixtures in Passenger Car Engines, SAE paper -24-0065.
[12] Andersson T. (2002). "Hydrogen Addition for Improved Lean Burn Capability on Natural Gas Engine", Rapport SGC 134 ISSN 1102-7371, Lund Institute of Technology.
[13] Bysveen, M. (2007). Engine characteristics of emissions and performance using mixtures of natural gas and hydrogen. *Energy*, *32*(4), 482-489.
[14] Park, C., Kim, C., Choi, Y., Won, S., and Moriyoshi, Y. (2011). The influences of hydrogen on the performance and emission characteristics of a heavy duty natural gas engine. *International Journal of Hydrogen Energy*, *36*(5), 3739-3745.

[15] Xu, J., Zhang, X., Liu, J., and Fan, L. (2010). Experimental study of a single-cylinder engine fueled with natural gas–hydrogen mixtures. *International Journal of Hydrogen Energy*, *35*(7), 2909-2914.

[16] Ma, F., Wang, M., Jiang, L., Deng, J., Chen, R., Naeve, N., and Zhao, S. (2010). Performance and emission characteristics of a turbocharged spark-ignition hydrogen-enriched compressed natural gas engine under wide open throttle operating conditions. *International Journal of Hydrogen Energy*, *35*(22), 12502-12509.

[17] Wang, J., Chen, H., Liu, B., and Huang, Z. (2008). Study of cycle-by-cycle variations of a spark ignition engine fueled with natural gas–hydrogen blends. *International Journal of Hydrogen Energy*, *33*(18), 4876-4883.

[18] Hu, E., Huang, Z., Liu, B., Zheng, J., and Gu, X. (2009). Experimental study on combustion characteristics of a spark-ignition engine fueled with natural gas–hydrogen blends combining with EGR. *International Journal of Hydrogen Energy*, *34*(2), 1035-1044.

[19] Dimopoulos, P., Rechsteiner, C., Soltic, P., Laemmle, C., and Boulouchos, K. (2007). Increase of passenger car engine efficiency with low engine-out emissions using hydrogen–natural gas mixtures: A thermodynamic analysis. *International Journal of Hydrogen Energy*, *32*(14), 3073-3083.

[20] Dimopoulos, P., Bach, C., Soltic, P., and Boulouchos, K. (2008). Hydrogen–natural gas blends fuelling passenger car engines: Combustion, emissions and well-to-wheels assessment. *International Journal of Hydrogen Energy*, *33*(23), 7224-7236.

[21] Escalante Soberanis, M. A., and Fernandez, A. M. (2010). A review on the technical adaptations for internal combustion engines to operate with gas/hydrogen mixtures. *International Journal of Hydrogen Energy*, *35*(21), 12134-12140.

[22] EC 2005. Directive 2005/55/EC of the European Parliament and of the Council of 28 September 2005.