LPT (Local Public Transport) electric buses: innovative solutions to reduce the energy absorption of auxiliaries

Fabio Orecchini[1], *Adriano* Santiangeli[1], *Fabrizio* Zuccari[1,*], *Fernando* Ortenzi[2], *Antonino* Genovese[2], and *Maria Pia* Valentini[2]

[1]CARe - Center for Automotive Research and Evolution, University Guglielmo Marconi, via Plinio 44, Rome 00193, Italy
[2]ENEA Italian National Agency for New Technologies, Energy and Sustainable Economic Development, Via Anguillarese, 301 - 00123 S.Maria di Galeria (Rome), Italy

Abstract. The focus of the study is the analysis and sizing of the air conditioning system on board the vehicle which operates in thermal transient for the duration of the typical mission, using "fan coil" type air conditioning devices powered by a hot or cold heat vector fluid loaded into "electro-thermal" charging station and the related ground cogeneration plant (at the BUS terminus). For winter air conditioning, it was assumed that a heat transfer fluid at a temperature of 90 ° C could be stored on board. This value allows the use of water as a heat transfer fluid without pressurizing the systems, minimizing costs and supply problems, and is compatible with the characteristics of ICE cogeneration systems. For summer air conditioning, it was assumed that ice or fluid at a temperature of -20 ° C could be loaded. Also in this case it was decided to operate with a common fluid, such as a solution of water and salt (e.g. calcium chloride $CaCl_2$). A comparative analysis of two solutions was carried out: the first involves the standard solution with BUS air conditioning system with heat pump powered by traction batteries charged by the grid and the second one analyzes the use of a high temperature Fuel Cell in a trigenerative configuration with refrigeration unit absorption fueled by the fumes of the FC. The trigeneration plant produces 100 kW of electricity via SOFC (Solid Oxide Fuel Cell) and, through an exchanger, water at 95 ° C which is stored on board the BUS for winter heating and feeds an absorption refrigeration machine that produces fluid at a temperature of -20 ° C for summer conditioning. For the two solutions, the savings of non-renewable primary energy and the reduction of GHG emissions compared to the standard solution (recharging the electric BUS from the network with on-board air conditioning powered by the traction batteries) are calculated through a WTW analysis. Consumption and emissions of electric powertrains, potentially for consumption and zero emissions, are closely linked to the methods of production and distribution of electricity.

* Corresponding author: f.zuccari@unimarconi.it

1 Introduction

The benefits of a fast charging station, with electric and thermal storage, have been evaluated in a reduced scale, designing and experimenting it on a minibus. A daily mission of a minibus has been fixed and all the cinematic parameters have been recorded, while all the electric parameters have been calculated using a simulator as used in [1].

Fig. 1. Line 117 in Rome.

The lined used for the simulations is the line 117 of Rome (Fig. 1), made with the Tecnobus Gulliver in the center of the city [1].

Three lines have been measured with a GPS tracker to collect the driving cycle and use it for the simulation in order to calculate the time to run the mission, the available time for the charging process, the energy consumption etc..

The line is made with 4 buses (4 bus/hour) and every bus start its mission one time per hour, but the time needed to start and return to the terminal is about 45 minutes, so there are up to 15 minutes to charge the battery with a new system with opportunity charge. An average load of 8 passengers has been assumed, based on the measurements made.

Table 1. Characteristics of the line 117 of Rome made with a Tecnobus Gulliver.

Parameters	Value
Time [s]	3,600
Average speed [km/h]	12.4
Distance [km]	8.34
Average power [kW]	2.78
Energy battery [kWh]	3.98
Specific energy battery [kWh/km]	0.481

The characteristics of the bus line are reported in Table 1. The mission of the bus has a distance of 8.34 km at an average speed of 12.4 km/h with a total consumption of 3.98 kWh (0.481 kWh/km).

A modified bus has been designed in order to test the fast charge technology with a ground storage based on flywheel.

 https://doi.org/10.1051/e3sconf/202131207013

The new bus will have the following characteristics:

- A pantograph to allow automatic charge when the bus reaches the terminal.
- A new storage system, with lower capacity but higher specific power in order to be charged at high power at the terminal. The technology chosen for this application is the LTO battery.
- A fast charger with the terminal with a flywheel storage, which is the purpose of the present work.

Fig. 2. Electric bus being part of the experimental test rig at ENEA Casaccia Research Center.

In a previous experimentation within the previous "Ricerca di Sistema Elettrico" program, to test the Flash Charge (at the bus stop) the bus has been equipped with a pantograph, as in Fig. 2 [2, 3].

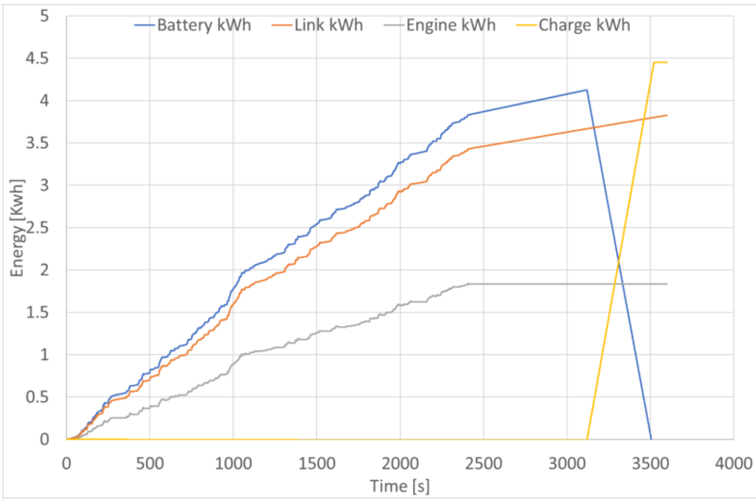

Fig. 3. Energy consumption and charged during a line 117 and recalculated for the "modified fast charge line" with a high specific power storage and a fast charge at the terminal with a flywheel as ground storage.

A new onboard storage, to be designed needs information about the mission of the bus with its energy consumption so the results from the acquisitions and the simulations above have be used and reported in Fig. 3.

The main information to design the onboard storage are the minimum energy required and the maximum discharge and charge power: the needed energy for the 117 line is about 4 kWh while the discharge power can be set to the maximum motor power (24 kW) and the charge power is the value of the charging station (40 kW). The limiting parameter, for this application is the power request and for the LTO battery, with 3C of maximum continuous current value, a capacity of about 15 kWh must be used [4, 5, 6].

2 Sizing of the bus conditioning system

The station, or terminus, originally designated only for the electric charging of vehicles, becomes an "electro-thermal" charging station, in which the vehicle transfers the "unloaded" thermal vector, replacing it with the "loaded" one, conditioned by the cogeneration system on the ground.

The vehicle's on-board air conditioning system operates in thermal transient for the duration of the mission-type using the "fan coil" type air conditioning devices suitably powered by the hot or cold thermal vector embarked in the "electro-thermal" recharge phase.

Regarding the winter air conditioning, it was assumed to be able to store fluid on board at a temperature of 90 ° C and to exploit its energy content up to a temperature of 45 ° C. It was decided to operate with water, intending to minimize the costs and supply problems, the environmental impact and the complications in managing the fluid from the plant engineering point of view.

The upper temperature limit responds to the choice of not introducing pressurization of the systems and, on the other hand, is well compatible with the characteristics of internal combustion cogeneration systems. The lower limit, on the other hand, responds to the operating needs of air-heater type air conditioners (fan coils), which can be advantageously sized to minimum values of inlet water temperature which are around 45 ° C.

Regarding the summer air conditioning it was assumed to be able to load a solution of water and salt (calcium chloride CaCl2) at a temperature of -25 ° C and to exploit its energy content up to a temperature of 10 ° C. The upper temperature limit is linked to the need to ensure the functionality of the dehumidification and air cooling.

Fig. 4 shows the diagram of the air treatment system serving the air-conditioned environment. The exchange of air inside the vehicle is often entrusted to the opening of the doors and natural ventilation, in ways that depend on the particular conditions of service and transport. In this analysis, it was considered useful to refer to a scheme based on forced ventilation, which allows to easily follow the thermohygrometric transformations in the different phases of the treatment.

The air conditioning system is sized to determine the heat output required by the air treatment section (cooling and dehumidification). The humid air conditions in section 2 are considered to be the same as those of the environment inside the conditioned room (design conditions).

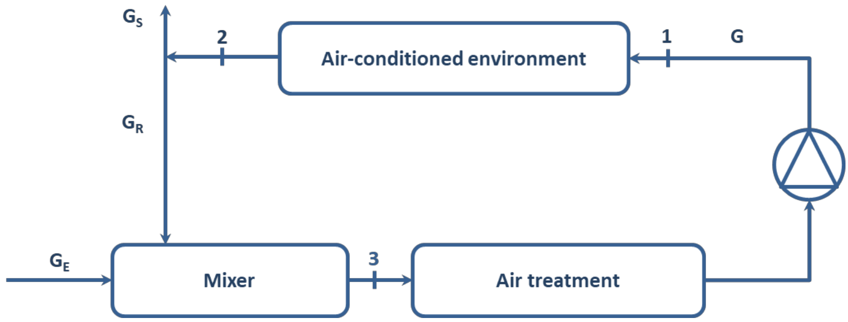

Fig. 4. Scheme of air treatment system serving the air-conditioned environment.

Parameters and quantities for the preliminary analysis are shown in Table 2.

Table 2. Parameters and quantities for the preliminary analysis of summer air conditioning system.

Parameters	**Value**
Target temperature [° C]	26
Target relative humidity	0.5
Outdoor air temperature [° C]	32
External relative humidity	0.75
Sensible load per transmission per volume unit [W/m^3]	35
Air-conditioned volume [m^3]	20
Sensible load for transmission [W]	700
Number of passengers	12
Sensible heat load per person [W / person]	100
Heat load produced by passengers [W]	1,200
Sensible heat load for infiltrations [W]	0
Sensible heat load for internal sources [W]	0
Total sensible heat load [W]	1,900
Steam flow rate introduced by passengers [kg / s]	0.0003
Steam flow rate introduced by infiltrations [kg / s]	0
Steam flow rate introduced by internal sources [kg / s]	0
Total latent heat load [W]	765
Total heat load [W]	2,625
Heat factor [W]	0.71

Table 3. Results of the preliminary sizing of summer air conditioning system.

Parameters	**Value**
Reference heat request [W]	5,000
Cold fluid inlet temperature [° C]	-25
Cold fluid return temperature [° C]	10
Specific heat of cold fluid [kJ/kg K]	2.8
Cold fluid flow [kg/s]	0.05
Density of cold fluid [kg/dm^3]	1.2
Cold fluid flow [dm^3/min]	2.55
Service time [min]	60
Cold fluid volume [dm^3]	153.06
Cold fluid mass ($CaCl_2$ solution) [kg]	183.67
Equivalent number of passengers	2.3
Overall efficiency of the air conditioning system	0.9
Storage heat energy [kWh]	5.56

Table 4 shows the parameters and quantities of interest for the preliminary analysis of the winter air conditioning system and Table 5 shows the results of the preliminary sizing of the winter air conditioning system.

Fig. 5 illustrates the layout of the BUS air conditioning system: at the terminus, the charge tank is filled with the heat transfer fluid (cold in summer, hot in winter) which feeds the heat exchanger and it is sent to the collection tank which is in turn emptied at the terminus. The logarithmic average temperature difference of the exchanger is equal to 27 ° C in the winter case and 56.8 ° C in the summer case; therefore the calculations will refer to the winter case (worst case).

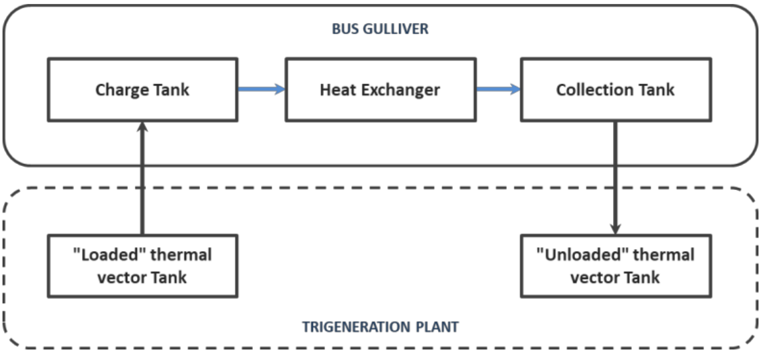

Fig. 5. Scheme of air treatment system serving the air-conditioned environment.

Table 4. Parameters and quantities of interest for the preliminary analysis of the winter air conditioning system.

Parameters	**Value**
Closed doors heat request [W/m^3]	100
Air-conditioned volume [m^3]	20
Heat load for transmission [W]	2,000
Target temperature [° C]	20
Outside temperature [° C]	0
Heat recovery efficiency	0.30
Exchange of hourly air volumes	30
Air exchange volumetric flow rate [m^3/h]	600
Volumetric mass of air [kg/m^3]	1.29
Exchange air flow [kg/s]	0.22
Heat load for air exchange [W]	3,025.05
Total heat load [W]	5,025.05

Table 5. Results of the preliminary sizing of the winter air conditioning system.

Parameters	**Value**
Total heat load [W]	5,000
Cold fluid inlet temperature [°C]	-25
Cold fluid outlet temperature [°C]	10
Cold fluid specific heat [kJ/kg K]	2.8
Cold fluid flow [kg/s]	0.05
Density of cold fluid [kg/dm^3]	1.2
Cold fluid flow [dm^3/s]	2.55
Service time [min]	60
Cold fluid volume (CaCl2 solution) [dm^3]	153.06
Equivalent number of passengers	2.3
Overall efficiency of the air conditioning system	0.9
Heat storage [kWh]	5.56

3 Sizing of trigeneration system

The plant considered (Fig. 6) is composed of a SOFC (Solid Oxide Fuel Cell) for the production of electricity in a cogenerative configuration: the hot exhaust fumes from the fuel cell are used in the winter for the production of hot water at a temperature of 95 ° C (used as a heat transfer fluid for heating the BUS) through a heat exchanger and in summer to feed (directly) an absorption refrigeration unit for the production of cold fluid (water and NaCl2 solution) at -25 ° C (used as heat transfer fluid for BUS cooling). The heat transfer fluids used are stored on the ground in insulated tanks in order to release the production times of these fluids (therefore the thermal power) from the time of loading and unloading of these fluids on board the BUS. When the bus arrives at the terminus, it "drains" the exhausted heat transfer fluid into one of the tanks and loads new fluid to be used for air conditioning on the other. The capacity of the tanks is 160 litres.

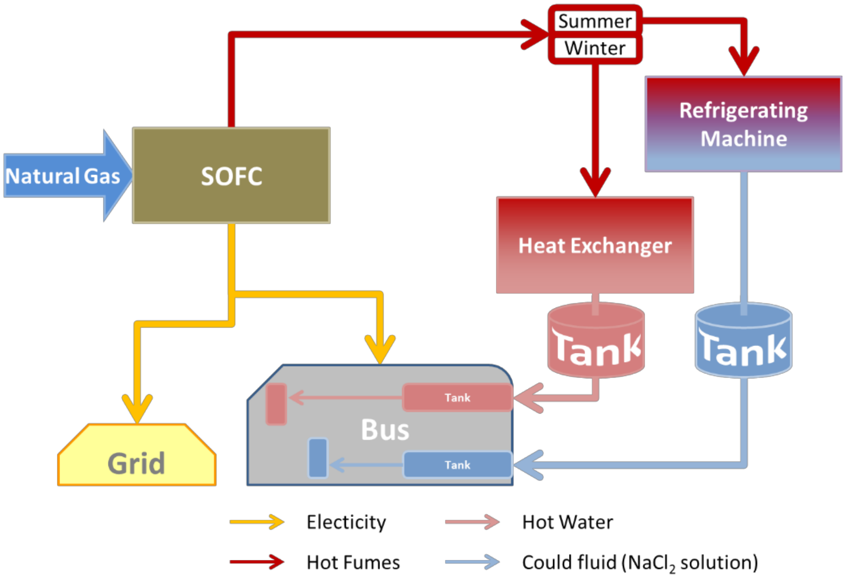

Fig. 6. Scheme of trigeneration system with fuel cells and absorption refrigeration machine.

In order to size the system on the basis of the required specifications (recharging the BUS traction battery and producing hot and cold fluid for air conditioning), a model of the fuel cells was built, based on literature data [7-15], considering however the commercial availability of the technologies used, to be used in the trigeneration plant with fuel cells and absorption refrigeration machine.

As for the absorption machine, from the analysis of the literature [16, 17] the operating efficiency was estimated under the specific conditions considered.

Below is the energy analysis of the system in the various operating conditions:

- Summer: electricity for recharging the traction batteries and heat for powering the absorption refrigeration machine for the production of ice for cooling the BUS;
- Winter: electricity for recharging the traction batteries and heat for powering the production of hot water (via an exchanger) for heating the BUS
- Spring / Autumn: electricity for recharging the traction batteries

In the configuration in which the system produces electricity for recharging the traction batteries and heat for powering the absorption refrigeration machine for the production of the heat transfer fluid at a temperature of -25 ° C for cooling the BUS (Fig. 7 *a*), the plant supplies 42.5 kW of electricity and 50 kW of heat with a natural gas consumption of 5.42 m^3/h: the electrical efficiency is equal to 40.5% while that of cogeneration is equal to 88.1%. In this configuration, due to the high thermal power required, the system produces excess electricity (11.5 kW that can be fed into the grid) compared to the need for recharging the BUS batteries (30 kW) and consumption of the absorption refrigeration machine.

In the configuration in which the system produces electricity for recharging the traction batteries and heat for the production of hot water at 95°C for heating the BUS (Fig. 7 *b*), the system supplies 37.5 kW (with a surplus of 7.5 kW compared to the 30 kW required to recharge the batteries) and 30 kW of heat with a natural gas consumption of 3.56 m^3/h: the electrical efficiency is 45.5% (much higher than in the previous case) while the cogeneration efficiency is 89.1% (in line with the previous case).

In the configuration in which the system produces only the electric energy for recharging the traction batteries (Fig. 7 *c*) the system operates under the same conditions and produces the 30 kW of electricity necessary to charge the BUS with a natural gas consumption of 3.56 m^3/h: the electrical efficiency is 45.8% (the highest of the three cases considered), but in the absence of heat demand the overall efficiency of the system is considerably lower and equal to the electrical efficiency (45.8%), but still high compared to other technologies in the same conditions.

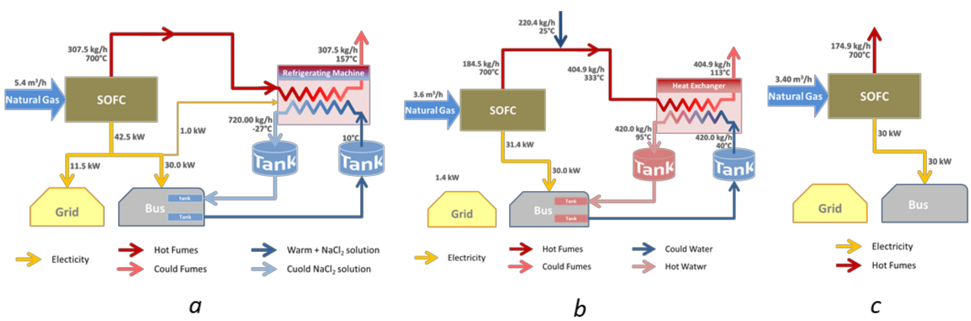

Fig. 7. Energy flows of the system in operation for summer (a), winter (b) air conditioning and in the absence of air conditioning (c).

4 WTW analysis and comparison

On the basis of literature data on the WTW analysis of natural gas and electricity withdrawn from the grid (considering the EU mix) [18, 19, 20], the non-renewable primary energy consumption (NRPEC) and the GHG emissions of the trigeneration and of the electricity consumption by the grid, were calculated. The natural gas consumption of the trigeneration plant are calculated considering consumption shown in the Fig. 7. The results of the NRPEC and GHG emission calculation are shown in Table 6.

In addition to the gross values of NRPEC and GHG, the consumption of non-renewable primary energy and the avoided GHG emissions were calculated on the basis of the energy fed into the grid; on the basis of these values, the net values of NRPEC and GHG were calculated. These values were compared with those obtained with a standard solution that provides for the conditioning of the BUS with a compression heat pump powered by the traction battery and the recharging of the batteries from the grid.

Table 6. Non-renewable primary energy consumption (NRPEC) and the GHG emission: comparison between the trigeneration plant and the standard solution.

Solution	**Gross NRPEC [MJ/year]**	**Gross GHG [kg/year]**	**Avoided NRPEC [MJ/year]**	**Avoided GHG [kg/year]**	**Net NRPEC [MJ/year]**	**Net GHG [kg/year]**
Trigeneration plant	1,296,549	14,944	589,643	27,242	706,906	0
Standard solution	1,040,260	48,060	0	0	1,040,260	48,060
Difference	+256,289	-33,116			-333,354	-48,060
Difference %	+25%	-69%			-32%	-100%

Not considering the consumption and avoided GHG emissions, compared to the standard solution, the use of the trigeneration plant shows an increase of 25% NRPEC (it is considered fossil natural gas, 100% non-renewable), but a reduction of 69% of GHG emissions. Considering the consumption and avoided GHG emissions, the studied solution has a reduction of 32% of NRPEC and is zero GHG emissions.

5 Conclusions

The solution studied which provides for the air conditioning system of the BUS with storage on board of a hot fluid (winter heating) and a cold fluid (summer cooling), with the production of electricity and heat transfer fluids in a trigeneration system at the terminus turns out to be decidedly efficient compared to the standard solution with BUS air conditioning system with heat pump powered by traction batteries charged by the grid. In fact, the study found that, considering the consumption and emissions avoided by the energy fed into the grid by the trigeneration plant, this solution is zero emissions and reduces the consumption of non-renewable energy by 69%.

Future developments of the presented study concern the users and technologies of the trigeneration plant. As far as users are concerned, a more detailed study of the "terminus" user can identify other possible on-site uses of electricity and heat, thus increasing the efficiency of this solution.

As regards the plant technologies, it is possible to analyze the results that can be obtained with the use of solutions that make it possible to improve the operating flexibility of the plant with high overall efficiencies. In particular, a widely studied and commercially available configuration is that of a SOFC integrated with a gas micro turbine (SOFC-mTG). This solution makes it possible to use the exhaust heat (at high temperature) of the SOFC when there is a request for heat or to use this heat to power but mTG in the case of no thermal demand, producing only electricity with yields exceeding 60 %.

References

1. Ortenzi, F.; Andrenacci, N.; Pasquali, M.; Villante, C. On the Hybridization of Microcars with Hybrid UltraCapacitors and Li-Ion Batteries Storage Systems. *Energies* 2020, *13*, 3230.
2. Fernando Ortenzi, Valutazione del consumo energetico e dell'energia di ricarica di un minibus in esercizio su una linea di trasporto pubblico urbano, Report Ricerca di Sistema Elettrico, Par 2019
3. Ortenzi, F.; Pasquali, M.; Prosini, P.P.; Lidozzi, A.; Di Benedetto, M. Design and Validation of Ultra-Fast Charging Infrastructures Based on Supercapacitors for Urban Public Transportation Applications. *Energies* 2019, *12*, 2348.
4. Cignini, F.; Genovese, A.; Ortenzi, F.; Alessandrini, A.; Berzi, L.; Pugi, L.; Barbieri, R. Experimental Data Comparison of an Electric Minibus Equipped with Different Energy Storage Systems. *Batteries* 2020, *6*, 26.
5. Fernando Ortenzi, Silvia Orchi, Maria Pia Valentini, Natascia Andrenacci and Alessandro Lidozzi, Technical and economical evaluation of fast charging infrastructures for electric buses, AIP Conference Proceedings 2191, 020123 (2019); https://doi.org/10.1063/1.5138856.
6. Ortenzi, F.; Pasquali, M.; Prosini, P.P.; Lidozzi, A.; Di Benedetto, M. Design and Validation of Ultra-Fast Charging Infrastructures Based on Supercapacitors for Urban Public Transportation Applications. Energies 2019, 12, 2348.
7. Fuel Cell and Hydrogen Energy Association (FCHEA): Hydrogen Fuel and Infrastructure Research & Development Workshop Report - August 2019
8. U.S. Department of Energy / Office of Energy Efficiency & Renewable Energy: Fuel Cell Technologies Market Report 2015, Fuel Cell Technologies Office agosto 2016
9. U.S. Department of Energy / Office of Energy Efficiency & Renewable Energy: Fuel Cell Technologies Market Report 2016, Fuel Cell Technologies Office ottobre 2017
10. Paolo Arcuri: Dimensionamento Ottimale di Impianti di Trigenerazione con Celle a Combustibile: Sviluppo di un Modello di Programmazione Non Lineare Mista-Intera e Confronto Tecnico Economico con Impianti Tradizionali in Utenze Residenziali. Tesi di Dottorato: Coordinatore Prof. Sergio Rizzuti, Supervisore Prof. Gaetano Florio - Scuola di Dottorato "Pitagora" in Scienze Ingegneristiche - Dottorato di Ricerca in Ingegneria Meccanica XXI Ciclo - Università della Calabria
11. Stephen J. McPhail, Jari Kiviaho & Bruno Conti: The Yellow pages of SOFC Technology: International Status of SOFC deployment 2017; IEA - Implementing Agreement Advanced Fuel Cells - Annex 32 – SOFC. Publisher: VTT Technical Research Centre of Finland Ltd, P.O. Box 1000, 02044 VTT, Finland. ISBN 978-951-38-8602-8 (printed); ISBN 978-951-38-8603-5 (online). Printed by Juvenes Print, Helsinki, Finland, 2017
12. Gabriele Ferruzzi: Analisi sperimentale e numerica di sistemi di conversione dell'energia basati su celle a combustibile. Tesi di Dottorato: Relatori Prof. Massimo Dentice D'Accadia, Prof.ssa Rita Mastrullo - Scuola di Dottorato in Ingegneria Industriale - Dottorato di Ricerca in Ingegneria dei Sistemi Meccanici XXXIII Ciclo - Università Degli Studi di Napoli Federico II
13. CORDIS Europa. Progetto: Molten Carbonate Fuel Cell (MCFC) 100 kW Cogeneration Power Plant: Coordinatore: ANSALDO Ricerche S.R.L.
14. R. J. Braun, P. Kazempoor: Chapt. 12 - Application of SOFCs in Combined Heat, Cooling and Power Systems - RSC Energy and Environment Series No. 7. Solid Oxide

Fuel Cells: From Materials to System Modeling. Edited by Meng Ni and Tim S. Zhao. The Royal Society of Chemistry 2013. Published by the Royal Society of Chemistry

15. W Wongsuwan, S Kumar, P Neveu, F Meunier. A review of chemical heat pump technology and applications, Applied Thermal Engineering, Volume 21, Issue 15, 2001, Pages 1489-1519, ISSN 1359-4311, https://doi.org/10.1016/S1359-4311(01)00022-9
16. M. Burer, K. Tanaka, D. Favrat, K. Yamada. Multi-criteria optimization of a district cogeneration plant integrating a solid oxide fuel cell–gas turbine combined cycle, heat pumps and chillers, Energy, Volume 28, Issue 6, 2003, Pages 497-518, ISSN 0360-5442, https://doi.org/10.1016/S0360-5442(02)00161-5
17. V Havelský. Energetic efficiency of cogeneration systems for combined heat, cold and power production, International Journal of Refrigeration, Volume 22, Issue 6, 1999, Pages 479-485, ISSN 0140-7007, https://doi.org/10.1016/S0140-7007(99)00010-9
18. J. R. Wooa, H. Choi, J. Ahn, "Well-to-wheel analysis of greenhouse gas emissions for electric vehicles based on electricity generation mix: A global perspective", Transportation Research Part D: Transport and Environment, Volume 51, Pages 340-350, https://doi.org/10.1016/j.trd.2017.01.005 March 2017.
19. R. Edwards, H. Hass, J. F. Larivé, L. Lonza, H Maas, D. Rickeard, "Well-To-Wheels analysis of future automotive fuels and powertrains in the european context", ISSN 1831-9424 (online), doi:10.2790/95533, Luxembourg: Publications Office of the European Union, 2014.
20. F.Zuccari, F. Orecchini, A. Santiangeli "*Biomethane use for automobiles towards a CO2-neutral energy system*", Clean Energy, Volume 5, Issue 1, March 2021, Pages 124–140, https://doi.org/10.1093/ce/zkab001