# Air bottoming cycle for hybrid solar-gas power plants

Fouad Khaldi*

Department of Physics, University of Batna, Batna, Algeria
* Corresponding author. Tel: +213 33819895, Fax: +213 33819895, E-mail: f.khaldi@univ-batna.dz

**Abstract:** Several solar-gas hybrid power plants based on the parabolic trough system are under construction in the MENA region and in Spain. The thermodynamic cycle of these plants is divided into topping cycle and bottoming cycle according to their temperature range. Since the solar collectors supply heat at a medium temperature level, up to 400°C, the existing technology uses a steam bottoming cycle (steam turbine). The present study aimed at investigating the thermodynamic feasibility of using air bottoming cycle (gas turbine) instead of the steam bottoming cycle. A thermodynamic scheme of solar air bottoming cycle was proposed. The case study considered an existing small size capacity gas turbine (<50 MW) as a topping cycle. The thermodynamic performance of the proposed solar air bottoming cycle was compared to two reference cases, without solar energy, a steam bottoming cycle and a conventional air bottoming cycle.

*Keywords:* *Solar-gas hybrid power plant, Air bottoming cycle, Thermodynamic analysis.*

## Nomenclature

**Acronyms**

| | |
|---|---|
| *ABC* | *Air Bottoming Cycle* |
| *AC* | *Air Compressor* |
| *ATC* | *Air Topping Cycle* |
| *MENA* | *Middle East and North Africa* |
| *C-ABC* | *Conventional Air Bottoming Cycle* |
| *CC* | *Combined Cycle* |
| *CD* | *Condenser* |
| *CS* | *Combustion System* |
| *DE* | *Deaerator* |
| *DR* | *Drum* |
| *EC* | *Economizer* |
| *EV* | *Evaporator* |
| *GR* | *Gas Recuperator* |
| *GT* | *Gas Turbine* |
| *GTC* | *Gas Topping Cycle* |
| *HRSG* | *Heat Recovery Steam Generator* |
| *IC* | *Intercooler* |
| *PM* | *Pump* |
| *S-ABC* | *Solar Air Bottoming Cycle* |
| *SBC* | *Steam Bottoming Cycle* |
| *SGHPP* | *Solar-Gas Hybrid Power Plant* |
| *SH* | *Superheater* |
| *SHX* | *Solar Heat Exchanger* |
| *ST* | *Steam Turbine* |

## 1. Introduction

Algeria, located in the Middle East and North Africa (MENA) region, is counted among the best insolated areas. Over the country land, estimated at 2.4 millions $Km^2$, the Sahara represents 86%. It is exposed yearly to a direct sun irradiation higher than 2000 $kWh/m^2$ gain from 3500 hours of sunshine. These solar potential and land resources are optimal for the implementation of concentrating solar power plants (CSPPs) [1]. In 2009 the power generating capacity in Algeria was over 9 GW, 98% of this capacity is provided by gas-fired plants, guaranteed in 46% by gas turbine power plants [2]. In according to the Algerian energy policy fixing the share of renewable energy to 5% by 2010, augmented afterwards to 8% by 2020 [2], and since Algeria's natural gas resources are among the largest in the world, solar-gas hybrid power plant (SGHPP) is more suitable than solar-only power plant. The former technology allows for guaranteed power delivery to the grid without the thermal storage needed for compensating the solar energy intermittency day/night [3].

Currently, a 150 MW plant is expected to start run very soon in Algeria with about 25 MW from solar field. Similar power stations are under construction in other MENA region countries [4], Egypt [5], Morocco, whereas in Iran [6, 7] and Jordan [8] SGHPPs are under consideration. The technology is based on the integrating of parabolic trough systems into combined cycles (CC) with gas topping cycle (GTC) and steam bottoming cycle (SBC). The parabolic trough systems represent the most mature solar thermal power technology, from both commercial and technical viewpoints, for mid-to-large scale grid connected power plants [9, 10]. The parabolic trough collectors can supply to the SBC a hot heat transfer fluid at medium temperature level of about 400 °C [11].

In recent years, intensive research works have been directed toward developing advanced bottoming thermodynamic cycles [12, 13]. The examined thermodynamic schemes were based on the combination of air cooling, intercooling, gas to gas recuperation and reheating [14-20]. For large-scale power generation, greater than 50 MW, it is proven that SBC is the most effective thermodynamic scheme than any other bottoming cycle [21-23]. However, for small-scale power gas turbines, generating less than 50 MW, suffering from limited efficiency, ABC can be competitive, thanks to size and economic constraints rendering unfavorable the use of SBC.
The present paper presents a conceptual analysis of SGHPP based on ABC. Air, instead of steam, is used in the bottoming cycle to recover both partially the energy supplied by the solar field and the energy from the gas turbine topping cycle exhaust. This plant will be dispensing with all the equipments related to steam power plant (high-pressure steam generator, steam turbine, condenser, pumps, water treatment plant, cooling towers, etc.). Hence, it is expected that the SGHPP based on ABC to be compact and less complex. In comparison to the steam turbine plant the gas turbine plant has some advantages: low capital investment cost and operating and maintenance cost, compact size, short delivery, high flexibility and reliability, fast starting and loading. In addition, gas turbines, free of water requirement, are more suitable to be implemented in high solar irradiation regions, limited in water resources.

A solar-air bottoming cycle (S-ABC) is proposed, analyzed and compared to two reference bottoming cycles (without solar energy), conventional air bottoming cycle (C-ABC) and steam bottoming cycle (SBC). The comparison is based on three main parameters, net output power, energy efficiency and exergy efficiency. For all scenarios, the same topping cycle was considered, an existing small size power turbine gas.

The thermodynamic simulations were performed by the flow-sheet program, “Cycle-Tempo”. This software is a freeware advanced tool for the analysis and optimization of energy systems, developed at the Delft University of Technology [24].

## 2. Thermodynamic simulations and evaluations

### *2.1. Thermodynamic bottoming cycles*

In the evaluation, for the three considered bottoming cycles the same gas turbine topping cycle was used. The GE M&I LM5000-PC(1) gas turbine model was chosen [24], it is a simple open cycle composed of a compressor (AC), a gas turbine (GT), a generator (G); all linked by a shaft, and a combustion system (CS). The cycle generates 34.450 MW, at ISO conditions (1.013 bars, 15°C, RH 60%, and $CH_4$ as fuel), with exhaust temperature and mass flow, respectively, 432.22 °C and 124.738 Kg/s. The energy and exergy efficiencies are respectively, 36.57% and 34.86%.

#### *2.1.1. Solar-air bottoming cycle*

The schematic flow diagram of the cycle is shown in Fig. 1. To limiting the number of heat exchangers incorporated in the cycle, just one intercooler (IC) was applied between two compressors, (AC1) and (AC2). The intercooler cooled the air exiting the first compressor (AC1) down to 40°C. After exiting the second compressor (AC2) the air was heated to 370°C in the solar heat exchanger (SHX). Afterwards, after expanding in the first gas turbine (GT1) the air penetrated into the recuperator (GR) for recovering some energy from the topping cycle flue gas before expanding in the second turbine (GT2). The effectiveness of the solar heat exchanger was set at 90%, whereas the air recuperator had the effectiveness of 85%. It assumed that the hot heat transfer fluid, coming from the solar collector, entered into the solar heat exchanger with about 395°C and then leaved with about 295°C. For the two compressors, the optimum pressure ration was 3.16 and 2.41, respectively. Both compressors and the turbine had an isentropic efficiency of 90%. The relevant air mass flow was estimated at 143 kg/s.

Heat delivered to the air in the solar heat exchanger is:

$$\dot{Q}_a = \dot{m}_a \Delta h , \qquad (1)$$

where $\dot{m}_a$ is the mass flow rate of air, and $\Delta h$ is the specific enthalpy gain of the air across the SHX. The solar irradiation input to the solar collector is calculated as:

$$\dot{Q}_s = \frac{\dot{Q}_a}{\eta_{sf}} , \qquad (2)$$

where $\eta_{sf}$ denotes the efficiency of the global conversion of solar irradiation to heat. This includes both the optical efficiency of the solar collector and the thermal efficiency characterizing the heat transportation from the solar collector to the SHX. The value of $\eta_{sf}$ is chosen to be 0.75, appropriate for the LS3 collector technology [25, 26].

The exergy input through the solar irradiation is determined by the formula [27, 28]:

$$\dot{E}x_s = \left[1 - \frac{4T_0}{3T_s}\left(1 - 0.28\ln\left(f\right)\right)\right]\dot{Q}_s , \qquad (3)$$

the symbols $T_0$ and $T_s$ are, respectively, the ambient temperature and the temperature of the Sun (5777 K), and $f$ is the dilution factor ($1.3\times10^{-5}$).
The energy and exergy efficiencies of the cycle are defined, respectively, as follows:

$$\eta_e = \frac{P_{el}}{LHV\dot{m}_f + \dot{Q}_s} \text{, and} \qquad (4)$$

$$\eta_{ex} = \frac{P_{el}}{\dot{E}x_f + \dot{E}x_s} , \qquad (5)$$

where $P_{el}$ is the total net power delivered by the cycle, and LHV, $\dot{E}x_f$ and $\dot{m}_s$ are, respectively, the lower heating value, the exergy rate and the mass flow rate of fuel.

### *2.1.2. Conventional air bottoming cycle*

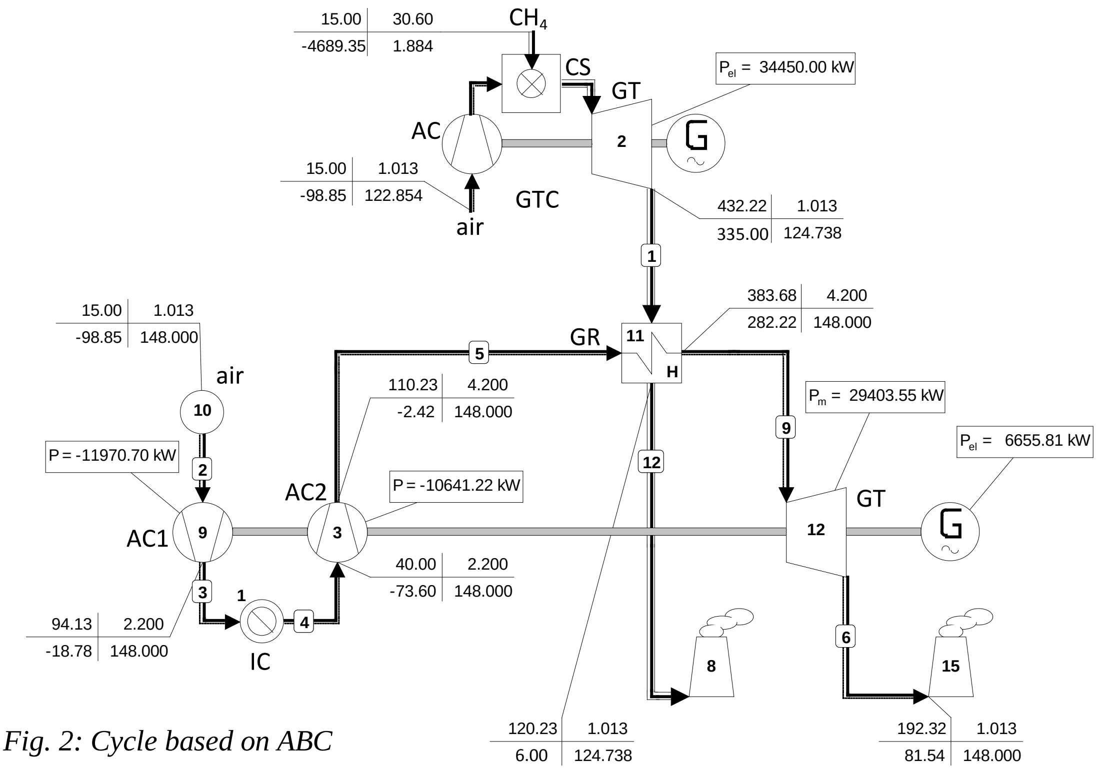


*Fig. 2: Cycle based on ABC*

As shown in Fig. 2, the air bottoming cycle without solar energy was examined. The C-ABC had the same characteristics as the S-ABC, except that the optimum pressure ration was 2.17 and 1.91, respectively. Also the air mass flow was fixed at148 kg/s.

### *2.1.3. Steam bottoming cycle*

Since the gas turbine topping cycle is of small size (<50 MW), a single-pressure HRSG was chosen. The HRSG was composed of an economizer (EC), an evaporator (EV), a superheater (SH) and a drum (DR). It had the pinch temperature of 20 °C and the approach temperature of 14°C. The superheater had the effectiveness of 87%. The superheated steam entered into the turbine (ST) at 404°C and 19 bars. The isentropic efficiency of the turbine was 85%. The pressure in the condenser (CD) was fixed at 0.074 bars, corresponding to saturation temperature of 40°C. Also, the deaerator (DE) pressure was set at 1.2 bars. More details about the cycle are presented in Fig. 3.

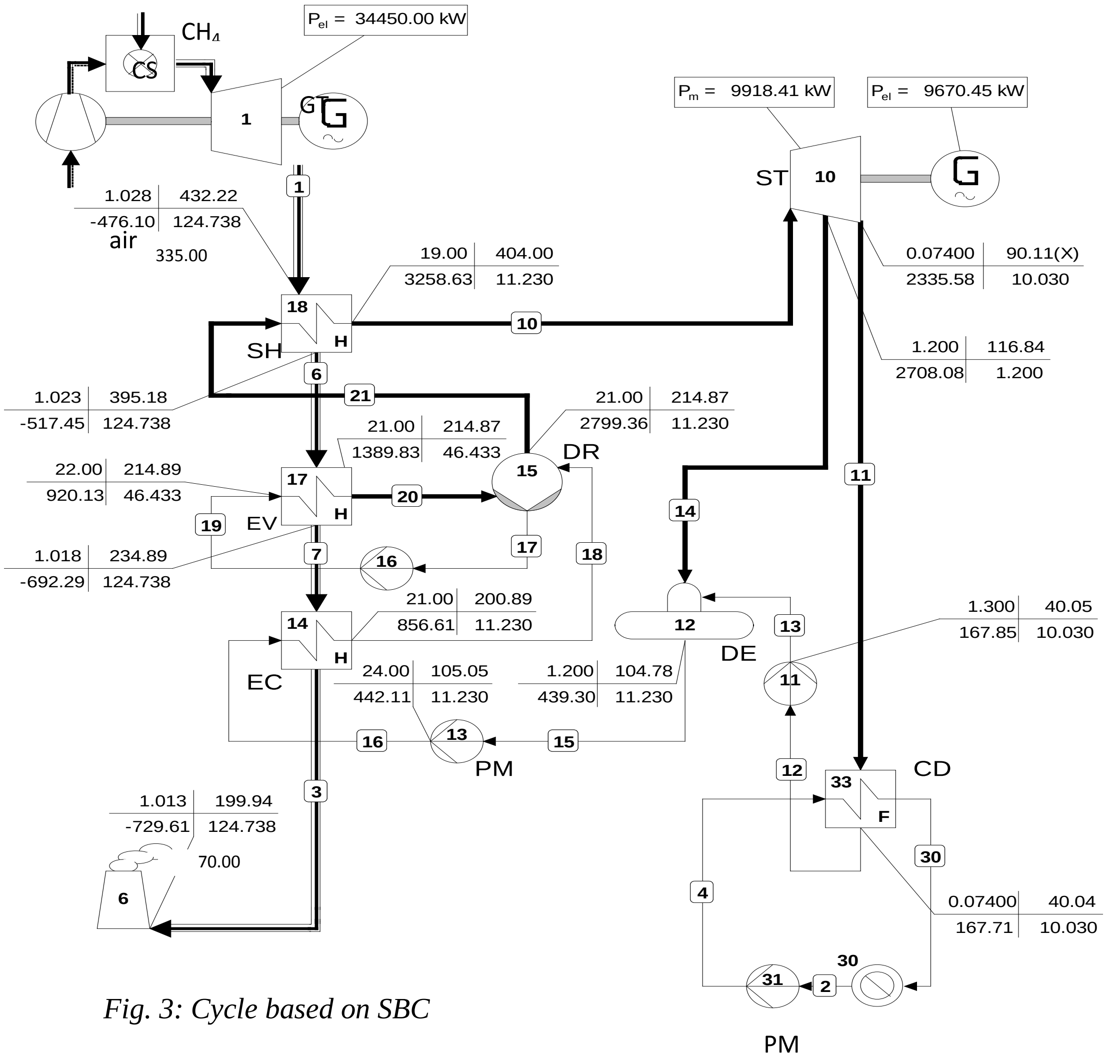


*Fig. 3: Cycle based on SBC*

## 3. Results and discussion

Main thermodynamic data related to the cycle performance, for the three examined bottoming cycles, are presented in Table 1. The S-ABC and SBC have nearly the same net output power; contributing to generate 44686 kW for the former and 44120 kW for the last, overtaking by far the C-ABC which delivers 41106 kW. However, the S-ABS is the less efficient cycle, with reference to the topping cycle, it augmented the cycle power by 28.07%, but it decreased the cycle efficiency from 36.56% to 31.87%. In contrary, the SBC is the more efficient cycle; with an energy efficiency of 46.78%, increasing then the topping cycle energy by 10.21 points. With energy efficiency of 41.60% the cycle based on the C-ABS improved the power generation by 19.32%. In term of exergy efficiency, relatively to the simple gas topping cycle the SBC and the C-ABC increase the cycle exergy efficiency from 34.36% (topping cycle), respectively, to 44.66% and 41.60%, the S-ABC decreased it slightly to 33.82%. Note that the cycle exergy efficiency associated to the S-ABC is greater than the energy efficiency.

The comparison between all the examined thermodynamic schemes depend on the relatively high number of thermodynamic parameters and combinations which can modify the performance of the cycle, i.e. turbines and compressors isentropic efficiency, heat exchangers effectiveness, pinch and approach temperature, condenser pressure, etc. The performance of the S-ABC can be improved by more cooling the air down in the intercooler, to less than 40°C, but this level of temperature is typical for cooling by dry air, adequate in regions poor in water resources. Further, at least one intercooler can be added, also an air to air recuperator can be incorporated to recover some energy of the exhaust air bottoming cycle (143 kg/s at 231 °C). Eventually, the complexity degree of the cycle presents a constraint for any possible modification.

Even, if the S-ABC and the SBC have a comparable performance, potentially the S-ABC can offers 143 k/s of relatively hot air, 230°C, which can be adequate for heat processes requiring pure air.

*Table 1. Performances of the three bottoming cycles, S-ABC, C-ABC and SBC.*

| | S-ABC | C-ABC | SBC |
|---|---|---|---|
| Net output power (kW) | 44686 | 41106 | 44120 |
| Energy efficiency (%) | 31.87 | 43.63 | 46.78 |
| Exergy efficiency (%) | 33.82 | 41.60 | 44.66 |

## 4. Conclusion

A case study of solar-gas hybrid power plant has been analysed thermodynamically. The topping cycle of the plant was chosen to be of small size capacity gas turbine (35 MW). An air-bottoming cycle has been proposed instead the well recognized steam topping cycle. Its thermodynamic scheme was based on the combination of intercooling, reheating and gas to gas recuperation. The performance evaluation of the examined cycle was based on the comparison to two reference cases (without solar energy), steam bottoming cycle and conventional air bottoming cycle, in terms of net output power and energy and exergy efficiencies. It was found that the solar-air bottoming cycle and the steam bottoming cycle (without solar energy) had comparable net out powers; whereas the conventional air bottoming cycle (without solar energy) had the smaller capacity generation. However, the steam bottoming cycle is the most efficient cycle, followed by the conventional air-bottoming cycle and afterward by far the solar-air bottoming cycle. The difference in efficiency between the solar-air bottoming cycle and the steam bottoming cycle is due to the definition of energy and exergy efficiency related to the solar cycle. Since the solar heat is provided from the solar irradiation which is free and never depleted, it is may be more practical to don't consider the solar heat energy/exergy as an additional input energy/exergy in the calculation of the energy/exergy efficiency concerning the S-ABC. In that case, the S-ABC becomes the more efficient cycle, with cycle energy and exergy efficiency, respectively, 47.43% and 45.50%.

## References

[1] V. Quaschning, Technical and economical system comparison of photovoltaic and concentrating solar thermal power systems depending on annual global irradiation, Solar Energy 44, 2004, pp. 171-178.

[2] Commission de Regulation de l'Electricité et du Gaz (Electricity and gas authority of Algeria), www.creg.org.dz, Annual Report 2010 (in French).

[3] Concentrated Solar Thermal Power-Now, European Commission, European Communities, 2005.

[4] A. Poullikkas, Analysis of power generation from parabolic trough solar thermal plants for the Mediterranean Region- A case study for the Island of Cyprus, Renewable and Sustainable Energy Reviews 13, 2009, pp. 2474-2484.

[5] M. A. H. El-Sayed, Solar supported steam production for power generation in Egypt, Energy Policy 33, 2005, pp. 1251-1259.

[6] R. Hosseini, M. Soltani, G. Valizadeh, Technical and economic assessment of the integrated solar combined cycle power plants in Iran, Renewable Energy 30, 2005, pp. 1551-1555.

[7] A. Baghernejad, M. Yaghoubi, Exergy analysis of an integrated solar combined cycle system, Renewable Energy 35, 2010, pp. 2157-2164.

[8] M. S. Al-Soud, E. S. Hrayshat, A 50 MW concentrating solar power plant for Jordan, Journal of Cleaner Production 14, 2009, pp. 625-635.

[9] Concentrating Solar Power-From research to implementation, European Commission, European Communities, 2007.

[10] Energy Technology Perspectives-Scenarios&Strategies to 2050, www.iea.org, 2008.

[11] A. Fernández-García, E. Zarza, L. Valenzuela, M. Pérez, Parabolic-trough solar collectors and their applications, Renewable and Sustainable Energy Reviews 14, 2010, pp. 1695–1721.

[12] Y. S. H. Najjar, M. S. Zaamout, Performance analysis of gas turbine air-bottoming combined system, Energy Convers. Mgmt. 37(4), 1996, pp. 399-403.

[13] M. Korobitsyn, Industrial application of the air bottoming cycle, Energy Conversion and Management 43, 2002, pp. 1311-1322.

[14] Y. S. H. Najjar, Comparison of performance for cogeneration systems using single-for twin-shaft gas turbine engines, Applied Thermal Engineering 17(2), 1997, pp. 113-124.

[15] Y. S. H. Najjar, Gas turbine cogeneration systems: a review of some novel cycles, Applied Thermal Engineering 20, 2000, pp. 179-197.

[16] P. A. Pilavachi, Power generation with gas turbine systems and combined heat and power, Applied Thermal Engineering 20 (15-16), 2000, pp. 1421-1429.

[17] Y. S. H. Najjar, Efficient use of energy by utilizing gas turbine combined systems, Applied Thermal Engineering 21, 2001, pp. 407-438.

[18] L. Chen, Y. Li, F. Sun, C. Wu, Power optimization of open-cycle regenerator gas-turbine power-plants, Applied Energy 78, 2004, pp. 199-218.

[19] A. Poullikkas, An overview of current and future sustainable gas turbine technologies, Renewable and Sustainable Energy Reviews 9, 2005, pp. 409-443.

[20] C. Ruixian, J. Lixia, Analysis of the recuperation gas turbine cycle with a recuperator located between turbines, Applied Thermal Engineering 26, 2006, pp. 89-96.

[21] A. L. Polyzakis, C. Koroneos, G. Xydis, Optimum gas turbine cycle for combined power plant, Energy Conversion and Management 49, 2008, pp. 551-563.

[22] A. Franco, C. Casarosa, On some perspectives for increasing the efficiency of combined cycle power plants, Applied Thermal Engineering 22, 2002, pp. 1501-1518.

[23] C. Carcasci, B. Facchini, Comparison between two gas turbine solutions to increase combined power plant efficiency, Energy Conversion & Management 41, 2000, pp. 757-773.

[24] Cycle-Tempo Release 5.0, 2007, Delft University of Technology, The Netherlands.

[25] G. Elsaket, Simulating the integrated solar combined cycle for cower plants application in Libya, MSc Thesis, 2007, Cranfield University, UK.

[26] M. J. Montes, A. Abánades, J. M. Martínez-Val, M. Valdés, Solar multiple optimization for a solar-only thermal power plant, using oil as heat transfer in the parabolic trough collectors, Solar Energy 83, 2009, pp. 2165-2176.

[27] E. Hu, Y. Yang, A. Nishimura, F. Yilmaz, A. Kouzani, Solar thermal aided power generation, Applied Energy 87 (9), 2009, pp. 2881-2885.

[28] M. V. J. J. Suresh, K. S. Reddy, A. K. Kolar, 4-E (Energy, Exergy, Environment, and Economic) analysis of solar thermal aided coal-fired power plants, Energy for Sustainable Development, 14 (4) 2010, pp. 267-279.