Applied Energy 109 (2013) 24–35

Contents lists available at SciVerse ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Environmental impact of decentralized power generation in Santa Clara City, Cuba: An integrated assessment based on technological and human health risk indicators

I. Herrera [a,*], J. De Ruyck [b], V.S. Ocaña [a], M. Rubio [a], R.M. Martínez [a], V. Núñez [c]

[a] Universidad Central "Marta Abreu" de Las Villas, Carretera a Camajuani km 5½, 54830 Santa Clara, Cuba
[b] Department of Mechanical Engineering, Faculty of Applied Sciences, Vrije Universiteit Brussel (VUB), Pleinlaan 2, 1050 Brussel, Belgium
[c] Meteorological Center of Villa Clara, Marta Abreu 59 altos, Santa Clara, Cuba

ARTICLE INFO

Article history:
Received 4 October 2012
Received in revised form 22 March 2013
Accepted 30 March 2013
Available online 25 April 2013

Keywords:
Power generation
Air pollution
Impacts mitigation

ABSTRACT

At present the worldwide energy market is dominated by fossil fuels, despite that it has been demonstrated to be a major source of environmental problems. In Cuba, about 96% of the power generation comes from fossil fuels, and 26% of this is produced by decentralized power stations (DPSs). DPS technology grew by a factor of six from 2005 to 2010, aiming to increase the efficiency in power generation and distribution, and to reduce the vulnerability on climate events. However, environmental impacts related to this technology, especially those impacts on human health, require a detailed analysis, considering that many DPSs have been located nearby densely populated areas.

This paper presents an analysis of the external effects related to gaseous emissions from decentralized power generation in Santa Clara City, Cuba. Also a perturbation analysis aiming to reduce such effects is presented. For this purpose a rather novel method called Integrated Assessment of Energy Supply (IAES) was developed. The IAES is built on the Impact Pathway Approach (IPA) and the System Perturbation Analysis (SPA), but including additional developments. The first of these concerns is the implementation of perturbations analysis to evaluate the external effects variation related to modifications in facility characteristics and operating conditions. E.g.: fuel type, efficiency, stacks geometry and microlocalization. Second, the exposure to polluting gases in the study area is determined taking into account the dispersion of pollutants, and the geographical distribution of the population. The exposure modeling is determinant to estimate human health impact. In this way it was found that northwest DPS cause the highest local impact on human health. This is associated with the pollutants concentration increase in densely populated areas. The higher CO_2 emissions correspond to the southeast DPS by a factor of 1.8 compared to the northwest DPS. However, the local impact related to the southeast DPS is lower, due to its location where downwind population is lower. A reduction potential on health impact of about 20% and 9% respectively was finally determined for northwest and southwest DPS.

Contents

* Corresponding author.
E-mail address: idalbertohm@uclv.edu.cu (I. Herrera).

0306-2619/$ - see front matter
http://dx.doi.org/10.1016/j.apenergy.2013.03.085

Nomenclature

λ	air excess coefficient
C	carbon
ICE	internal combustion engine
CO	carbon monoxide
CO_2	carbon dioxide
CRF	concentration–response function
DPS	decentralized power station
EED	effective energy demand
EIA	environmental impact assessment
EPA	Environmental Protection Agency
g	gram
GBD	global burden of disease
GHG	greenhouse gases
IAES	Integrated Assessment of Energy Supply
IPA	Impact Pathway Approach
LCA	Life Cycle Assessment
M	molar mass
MAC	maximum allowable concentration
NO	nitrogen monoxide
NO_2	nitrogen dioxide
NO_x	nitrogen oxides
PM_{10}	particulate matter $\leqslant 10\ \mu m$
REC	raw energy consumption
SO_2	sulfur dioxide
SPA	System Perturbation Analysis
SPG	station for power generation
Toe	ton of oil equivalent = 41,900 MJ
USG	Unhealthy for Sensitive Groups
UTM	Universal transverse Mercator
VU	very unhealthy

Subscripts

eq	equivalent
f	fuel
g	gasses

1. Introduction

Fossil energy use has been recognized as a major anthropogenic source of air pollutants [1–4]. At present, about 67% of the world electricity production comes from fossil fuels [5], in Cuba, these represent about 96% in the fuel mix for this activity [6].

This consumption pattern has been driven by the market forces. On the light of traditional analysis for energy supply alternatives, fossil energy appears to be the cheapest option, especially for developing countries, where the external effects are still usually underrated in decision making, considering in this process only internal costs [7]. However, including external effects assessments in energy supply scenario analysis is beneficial to society, e.g. competitiveness decrease of fossil fuels against renewable sources. This generates potential for energy efficiency increase and to reduce pollutants emission to the environment [3,8,9].

Generally, gaseous emissions to the atmosphere are regulated by setting emission standards to establish the maximum allowable emissions for each technology, the so called technology-based standards [10,11]. Other air quality standards to protect human health are set to regulate the maximum allowable concentration of pollutants in air. However meeting emission standards does not necessarily mean meeting air quality standards. This is particularly true when several emission sources are closely located. In such cases, to elucidate the specific burden of each source in air pollution, and its potential external effects is important. To this end sophisticated analyses including pollution dispersion modeling are needed.

External effects of energy production are the outcome of complex interactions of different nature, including technological, social, economic, and physical. Handling cause–effects interactions in order to achieve an appropriate representation is a complex task only achievable by huge modeling efforts. This makes it difficult to establish a universal tool for environmental impact assessment of energy systems or scenarios, but many tools already exist. The Impact Pathway Approach (IPA) developed in the frame of ExternE [3], the Life Cycle Assessment (LCA) [12] and the System Perturbation Analysis (SPA) [13] are important tools.

The methodology developed within the ExternE framework focuses on the assessment of externalities related to energy conversion, mainly for the electricity generation sector, in terms of marginal values [2]. This may be perfect for the introduction of externalities into expansion-planning models, but not for including environmental criteria in operational models, neither for assessing impacts variations due to perturbations in operational variables of energy facilities. Since ExternE methodology estimates the externalities considering the average concentrations in the study domain, to distinguish the spatial distributions of impacts due to the spatial distribution of pollutants concentration and population is difficult.

Convenience of LCA to probe the environmental performance of processes, including heat and power generation, has been well demonstrated. However, it tends not to be specific on the calculation of impacts in regard to geographical location. E.g. CO_2 emissions from combustion cycles are accounted in terms of net emissions and categorized according to four population density levels: remote, low populated, medium populated and densely populated [14]. In the same way the SPA looks to geographical system balances of resource consumption and emissions, but the spatial resolution still being country scale [13]. Neither LCA nor SPA considered local scale impacts.

On the other hand, the aforementioned methodologies were created by and for developed countries, for that reason their application in developing countries is limited, due to the complementary studies and large data needed to estimate environmental impacts. However this kind of analysis is required in both developed and developing countries, in view of the facts that developing countries usually have less clean technologies and consume more polluting energy sources than developed nations [4].

With this purpose a rather novel method called Integrated Assessment of Energy Supply (IAES) was developed. The IAES is builds on SPA [13] and the IPA [3], but includes some modifications and additional developments. For example, SPA is based on life cycle analysis, and its spatial resolution for impacts assessment does not make distinction about local siting of technologies. For IAES local siting of technologies is relevant, because gases emissions and their impacts on human health are tracked from release point to final receptor. As a common feature in both analyses the effective energy demand is kept constant for scenarios assessment. The main difference with IPA is the choice of emphasis, the external cost for IPA, and to determinate impacts and mitigation choices through perturbation analysis for the IAES. The IAES allows, through the high spatial resolution of the analysis, identifying local areas where major exposures and impacts are generated, the individual responsibility of polluters, as well as location and operating conditions influence on impacts variation.

Important researches on local impacts assessment of energy have been done by Wang and Mauzerall [15], Turtós Carbonell [4], and Mahapatra et al. [7]. In these works the impacts on health due to concentration variations of pollutants related to specific emission sources were estimated. These estimations were based on the average concentration increase in the study domain and the total population exposed. On this regard some additional contributions are made in the present work. First, the spatial variation of the concentration in the study domain is considered in the impact analysis. Second, the spatial distribution of the population is also taken into account. Finally, these developments allow for assessing the effects on health impact considering the location of the emission sources and the influence of small perturbations in operating conditions.

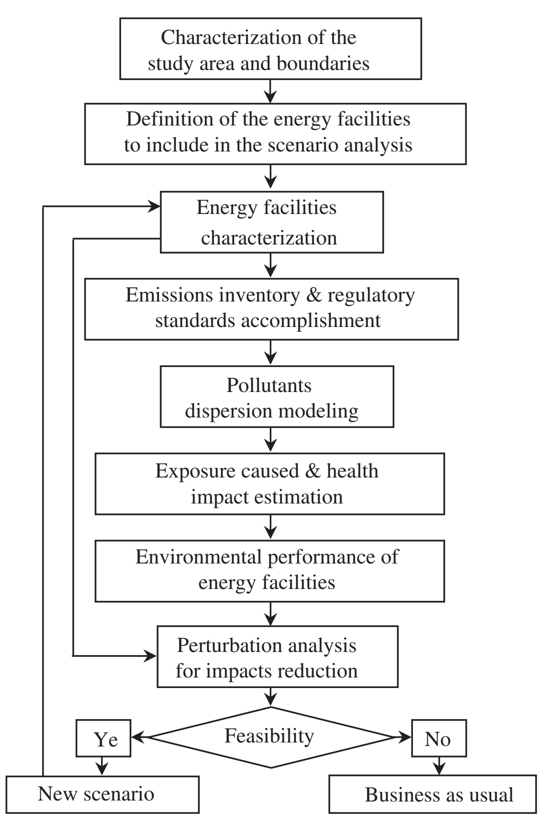

Fig. 1. Main steps of an Integrated Assessment of Energy Supply scenario.

This work aims to analyze whether impacts of gaseous emissions from decentralized power generating plants in Santa Clara City are of little or no concern according to current knowledge, as well as to evaluate mitigation choices. The high-priority impacts are human health related to air pollution and global warming potential as those are recognized the most important impacts of the energy conversion via combustion [3,9].

The current study is carried out in Santa Clara City. This is one out of many Cuban cities affected by air pollution, where air quality has been diagnosed as Unhealthy for Sensitive Groups (USG) [16]. All decentralized power stations in the city are included in the analysis: Two fuel oil fueled and two diesel fueled facilities, with a total installed power of 84 MW. The assessment was carried out for the year 2010. In addition to decentralized power stations, 31 emission sources [17] have been identified within the survey area by the environmental authorities, but the burden of decentralized power stations in terms of fuel demand represents 85%, which rises especial attention to these emissions sources [17].

2. Methodology

Energy services are a cornerstone in modern society, but besides the welfare it provides, some undesirable impacts are generated. The most significant impacts are the global warming, due to GHGs emission, and human health risks, due to local increased concentrations of air pollutants such as SO_2, NO_x, PM, and CO. Other impacts on ecosystems and materials can be linked to energy use [3,9].

To achieve a healthy balance between energy supply alternative and related impact is crucial for sustainable development. However, in a given scenario multiple variables and their interactions affect this balance, e.g. effective energy demand, energy conversion technologies and its efficiency, raw energy consumption, emission rate of polluting gases, emissions source location, local topography, demography and meteorology. In this section for the assessment of local energy supply scenarios, considering the aforementioned variables a methodology is presented. The methodology is conceived as a 'bottom-up' approach. It has been developed to support decision making in local energy policy including environmental criteria such as population exposure to polluting gases released by energy conversion via combustion, related human health risk and GHGs emissions.

The methodology has the following steps: (1) characterization of the study area, (2) definition of the energy facilities to include in the scenario analysis, (3) characterization of the energy facilities, (4) Emissions inventory and regulatory standards accomplishment, (5) pollutants dispersion modeling, (6) estimation of the exposure caused and impact on health, (7) environmental performance of energy technologies, (8) perturbation analysis for impacts reduction and (9) feasibility analysis to build new scenarios. The main steps are presented in Fig. 1, and below are described in details.

2.1. Formulation for estimation of impact on health and exposure generated

A consensus has been emerging among public health experts that air pollution, even at current ambient levels, aggravates morbidity (especially respiratory and cardiovascular diseases) and leads to premature mortality [3,18–20]. Generally, the assessment of air pollution impacts on human health is performed through concentration–response functions (CRFs). Those functions correlate the increment of ambient pollutant concentration, during a given time period of exposure, with the corresponding health risk increment. CRFs are determined by epidemiological studies using statistical analysis. Recent epidemiological studies have found approximately linear correlations between the increment of pollutants concentration and health risk, in a range applicable for ambient concentrations, without a threshold below which no adverse effects could be expected [21–26]. These findings support the statement of Eq. (1), which is typically used to estimate the impact variations on human health related to determined changes of outdoor air pollution [3,18,27].

$$\Delta I_{(A;q)} = Pop_{(A;q)} \cdot \Delta C_{(A;q)} \cdot S_{CR(q)} \tag{1}$$

where $\Delta I_{(A,q)}$ is the impact variation on human health in the area $A = \Delta x$, Δy related to the increase in the concentration of the pollutant q. $Pop_{(A,q)}$ Population within the area A exposed to the pollutant q expressed in inhabitants. $\Delta C_{(A,q)}$ is represents the increases in the concentration of the pollutant q in the area A μg/m^3. $S_{CR(q)}$ is the slope of the concentration–response function for the pollutant q. S_{CR} depends on the impact assessed, and generally can be extrapolated from the literature or calculated based on life data tables and epidemiological information.

In the present work, loss of life expectancy from general chronic mortality due to the increased exposure to PM_{10} is the impact on human health assessed which is expressed as years of life potentially lost per year (YOLL/yr).

The population data have been gotten from the Municipality's Statistic Office [28], based on these data a population distribution matrix for the study domain has been generated.

The increases in the concentrations generated by the emission sources included in the analysis are determined by pollutants dispersion modeling, in this way matrices of incremental pollutants concentrations for the study domain are determined. Established the matrices of population distribution and incremental concentrations Eq. (1) can be developed and written as follow:

$$\Delta I_{n(A;q)} = S_{CR(q)} \iint Pop_{(\partial x,\partial y)} \cdot \Delta C_{n(\partial x,\partial y;q)} dxdy \tag{2}$$

where $Pop(\partial x, \partial y)$ is the population in the area fraction $\partial A = \partial x \cdot \partial y$ in inhabitants, the area fraction size depend on the spatial resolution defined for the receptors grid in the study domain; $\Delta C_{n(\partial x,\partial y;q)}$ $dxdy$ is the incremental concentration in μg/m^3 of the pollutant q in the fraction of area ∂A due to emissions from n sources; $S_{CR(q)}$ is the slope of the concentration–response function for general chronic mortality. In this study the one suggested by ExternE [3] (SCR = 4.0E−4 YOLL/inhabitants yr μg/m^3) for PM_{10} is adopted. This value was determined by recalculation of loss of life expectancy due to relative risk increase of 1.06% per 10 μg/m^3 of $PM_{2.5}$ given by Pope et al. [23].

The use of chronic mortality to assess impact on health is based on results from several surveys on the effects on health of air pollution derived from combustion cycles. Some key finding from these surveys are the following: chronic mortality due to PM_{10} exposure tends to dominate the overall burden of diseases [27], accounting at least for 80% of health effects [3]; compared with chronic mortality, acute mortality means only a small fraction, in any case included in chronic mortality; under certain assumptions it has been demonstrated that acute mortality represents only about 1% of the total impact on mortality caused by the exposure to particulate matter [29].

Table 1
CRFs of health outcome as %/10 μg/m^3.

Pollutant	Health end point	Value (95% CI)			Source
		Low	Central	High	
NO_2	Total acute mortality	0.47	0.62	0.78	Stieb [28]
SO_2	Total acute mortality	0.28	0.36	0.48	Stieb [28]
PM_{10}	Total acute mortality	0.6	1	1.5	Ostro [3]

Due to the limitations in the national epidemiological surveys to establish acceptable accurate CRFs the values used in this work have been extrapolated from international reports. In this way an extensive study of the CRFs derived from meta-analysis of studies of air pollution and mortality from around the world was made [23,27,30,31]. The most relevant outcome of the nationals surveys, which have found concentration–response correlations in the range reported internationally were also taken as Refs. [4,32].

Assuming that the impact on human health variation (ΔI) related to certain increase in the concentration of the pollutants mix is the sum of the impact attributable to each specific pollutant; ΔI can be estimated assessing the impact related to the concentration increase of NO_2, SO_2 and PM_{10}:

$$\begin{aligned}\Delta I_{n(A;NO_2,SO_2,PM_{10})} = {} & S_{CRNO_2} \iint Pop_{(\partial x,\partial y)} \cdot \Delta C_{n(\partial x,\partial y;NO_2)} dxdy \\ & + S_{CRSO_2} \iint Pop_{(\partial x,\partial y)} \cdot \Delta C_{n(\partial x,\partial y;SO_2)} dxdy \\ & + S_{CRPM_{10}} \iint Pop_{(\partial x,\partial y)} \cdot \Delta C_{n(\partial x,\partial y;PM_{10})} dxdy\end{aligned} \tag{3}$$

where $\Delta I_{n(A;NO_2,SO_2,PM_{10})}$ is the impact on human health variation in YOLL/yr related to the concentration increase of the pollutants NO_2, SO_2 and PM_{10} due to emissions from n sources.

Being defined the pollutants to assess in the analysis and their CRFs, it is possible to express the pollutants species concentration in terms of an equivalent concentration by taking a specific pollutant as reference. This can be done using Eq. (4), e.g. which considers PM_{10} as reference.

$$\Delta C_{nPM_{10}eq(\partial x,\partial y;q)} = \Delta C_{n(\partial x,\partial y;q)} \cdot \frac{CRF_q}{CRF_{PM_{10}}} \tag{4}$$

where $\Delta C_{nPM_{10eq}(\partial x,\partial y;q)}$ is the concentration increase of the pollutant q in the fraction of area ∂A, due to emissions from n sources expressed as PM_{10eq} in μg/m^3; CRF_q is the change rate occurrence of the assessed impact due to the concentration change of the pollutant q in %/μg/m^3; CRF_{PM_10} is the change rate occurrence of the assessed impact due to the concentration change of PM_{10} in %/μg/m^3.

In this work, the CRFs for total acute mortality derived from meta-analysis of time series studies of air pollution and mortality reported by Stieb et al. [31] and Ostro [27] has been adopted for use in Eq. (4). These are given in Table 1.

The equivalence factors, taking as reference the PM_{10} and based on the central value given in Table 1, are: 1 μg/m^3 PM_{10} = 1.61 μg/m^3 NO_2 = 2.78 μg/m^3 SO_2.

Further developments in the epidemiology and toxicology field on health impact estimation will allow a better definition of the specific impact attributable to each pollutant.

Now Eq. (3) can be written as follow:

$$\Delta I_{n(A;PM_{10}eq)} = S_{CRPM_{10}} \iint Pop_{(\partial x,\partial y)} \cdot \Delta C_{n(\partial x,\partial y;PM_{10}eq)} dxdy \tag{5}$$

where $\Delta C_{n(\partial x,\partial y;PM_{10eq})}$ is the sum of all concentrations expressed as PM_{10} equivalent in μg/m^3.

2.1.1. Exposure estimation

In Eq. (5) elements within the integral can be used as indicators of the total incremental exposure $\Delta E_{n(A;PM_{10eq})}$ expressed in μg/m^3 PM_{10eq}·inhabitants. This indicator considers the spatial distribution of the incremental concentrations and the population exposed, as suggested in

$$\Delta E_{n(A;PM_{10}eq)} = \iint Pop_{(\partial x,\partial y)} \cdot \Delta C_{n(\partial x,\partial y;PM_{10}eq)} dxdy \tag{6}$$

By the Hadamard product of the population distribution matrix and the incremental concentration matrix for PM_{10eq} a total incremental exposure matrix is determined. Based on this matrix the exposure pattern in the study domain can be elucidated, and a total exposure map can be built. This is valuable information to determine priorities in mitigation actions.

The total incremental exposure given in Eq. (6) can be determined for a single source by Eq. (7) written bellow for instance to determinate the exposure indicator related to the source 1, in a context where n sources are included in the analysis.

$$\Delta E_{n_1(A;\mathrm{PM}_{10}eq)} = \Delta E_{n(A;\mathrm{PM}_{10}eq)} - \Delta E_{n_{2-i}(A;\mathrm{PM}_{10}eq)} \quad (7)$$

where $\Delta E_{n_1(A;\mathrm{PM}_{10eq})}$ is the total annual average exposure variation caused by source 1; $\Delta E_{n(A;\mathrm{PM}_{10eq})}$ is the total annual average exposure variation caused by all sources; and $\Delta E_{n_{2-i}(A;\mathrm{PM}_{10eq})}$ is the total annual average exposure variation caused by all source excluding source 1.

2.1.2. Environmental performance of energy facilities

Three indicators to characterize the environmental performance of energy facilities are used in the present work. First, the impact variation on human health caused by the PM_{10} emissions from the energy facilities which is estimated by Eq. (2) in terms of loss of life expectancy involved in general chronic mortality due to PM_{10} exposure. Second, the total incremental exposures generated per MW h of effective energy demanded, which is called marginal incremental exposure. And finally the CO_2 emissions are assessed.

The aforementioned indicators should be determined for each specific source and for the group of sources included in the analysis.

The marginal incremental exposure $\Delta Em_{n_i(A;\mathrm{PM}_{10eq})}$ expressed in $\mu g/m^3\ PM_{10eq}$·inhabitant/MW h is calculated as follow:

$$\Delta Em_{n_i(A;\mathrm{PM}_{10eq})} = \Delta E_{n_i(A;\mathrm{PM}_{10eq})}/\mathrm{EED} \quad (8)$$

Potential impacts on health are an important guide for policy makers. Its estimation can indicate the magnitude of pollution problem related to a specific source or a group of them, and provide the necessary data to develop successful strategies for air pollution control. The impact on health can be assessed as guiding indicator to set environmental targets, and estimate the level of effort that is necessary in a given area to achieve them. Also it can be a signal to prioritize interventions, balancing environmental, social and economic benefits. This indicator allows rank the emission sources according to the specific impact attributable to each source, including the technological, environmental and social aspects.

The marginal incremental exposure allows to determine the level of exposure generated by a specific source or a group of them per MW h of effective energy demanded. This is a useful indicator to assess the location effect of the facilities, allowing for establish operating strategies in order to generate the lowest exposure of the population to polluting gases, or identify the best possible location for new facilities.

3. Case-study, characterization of the study area and boundaries

The main variables to characterize the study area are: Location, boundaries, demography, meteorology and topography. To define the location and boundaries, the spatial domain constraint in the model selected to simulate pollutants dispersion has to be considered. As this methodology was developed for the assessment of scenarios at local scale a Gaussian plume model has been selected. This limits the study domain to 100 × 100 km maximum. This

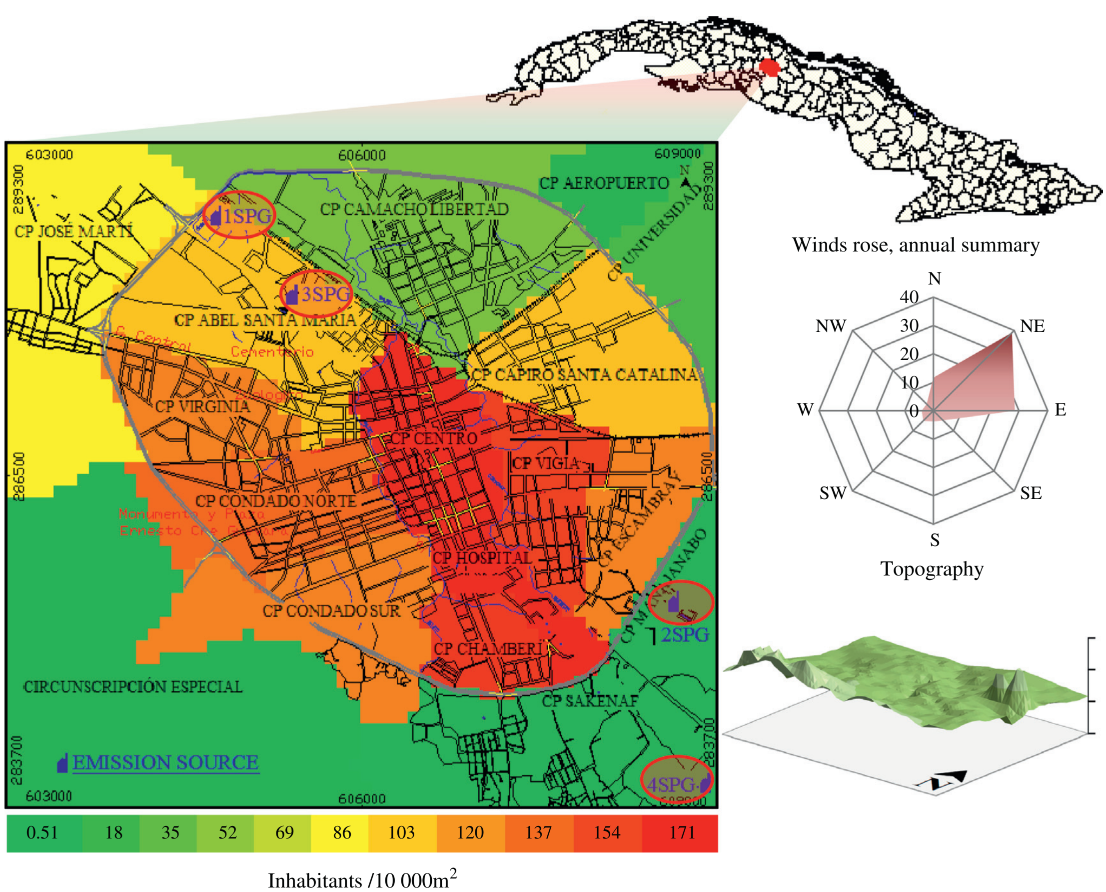

Fig. 2. Santa Clara, study area: 6 × 5.6 km; location: 22°.24′.00″N, 79°.58′.00″W. Representation of the population density distribution, location of emission sources, meteorology and topography. *Source*: Elaborated by the author with data from the Municipality Statistics Office [28] and Meteorological Center of Villa Clara [35].

Table 2
Generals data of the energy facilities included in the scenario analysis.

Facilities	Location	Installed power (MW)		Main fuel	Units per stack	Description
		Total at plant	Per unit			
1SPG	604623; 288631	20.4	1.7	Heavy fuel oil	4	Package power stations, based on set of internal combustions engines
4SPG	608724; 285313	20.4	1.7		4	
2SPG	605321; 287897	28.8	1.8	Diesel	1	
3SPG	608835; 283882	14.4	1.8		1	

[a] Location in UTM system.

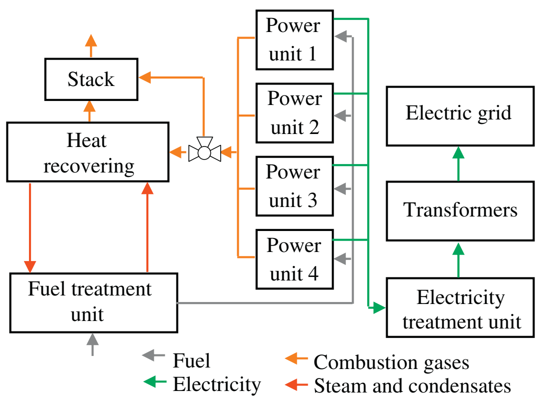

Fig. 3. Representation of one power generation cell.

choice was made in response to the necessity to manage the local air pollution problem caused by energy use.

Santa Clara City is the geographic area where the present survey is carried out; it is the capital of the urban system of the province of Villa Clara and one of the five most important cities in the country. The area of the city is 40.6 km^2, with a population of about 210,000 inhabitants in 56,300 residences. The habitat and services area covers 69% of the urban zone, industry 26% and green areas 1%. Population density in the city is 5180 inhabitants per km^2 [33]. Fig. 2 shows the population distribution and size of the study area, which cover 33.6 km^2 and a population about 166,400 inhabitants. Besides, the wind rose plot and the topography are shown. The population involves in the present study represent 70% of the total in the municipality.

Meteorology and topography are determinants factors in the gaseous pollutants dispersion. In this way, detailed data of these elements for dispersion modeling are required. In this survey a topography grid with a resolution of 100 × 100 m has been used. Ground-level concentrations of contaminants are primarily controlled by two meteorological elements: wind direction and speed (for transport), and turbulence and mixing height of the lower boundary layer (for dispersion) [34]. For this survey, hourly meteorological data including wind direction and speed, environment temperature, stability class and mixing height was provided by the Meteorological Center of Villa Clara [35].

3.1. Definition of the energy facilities to be included in the scenario analysis

The current survey includes the decentralized power generation facilities in Santa Clara City, Cuba. Specifically two fuel oil fueled power station, designated with the acronyms 1SPG and 4SPG, and two diesels fueled stations designated with the acronyms 2SPG and 3SPG. The facilities location is shown in Fig. 2 highlighted with a red circle. It should be noted that three of these stations are located nearby densely populated areas. On the other hand, in terms of raw energy consumption these facilities represent 85% of the fuel consumption corresponding to the 31 major polluters in the city [35]; in addition, an important fraction (74%) of this consumption is fuel oil, one of the most polluting energy carriers.

Table 4
Main operating parameters of the power stations.

Power station	Installed power (MW)	Operating hours (h_{motor}/yr)	Raw energy consumption (toe/yr) [MW h/yr]	Effective energy demand (MW h/yr)
1SPG	20.40	27,918	8330 [96,954]	40,342
2SPG	28.80	17,520	5436 [63,269]	23,652
3SPG	14.40	8760	2718 [31,635]	11,826
4SPG	20.40	49,120	14,656 [170,585]	70,978
All	84	–	31,141 [362,443]	146,798

Net caloric values used in the calculation were for DO: 42.8 MJ/kg, HFO: 41.2 MJ/kg, fuel of reference: 41.9 MJ/kg.

3.2. Energy facilities characterization

The characterization of the energy facilities should include the following specifics: facilities location, installed capacity, effective energy demand, raw energy consumption, load factor, fuel type, combustion conditions, hourly fuel consumption, and energy efficiency. These are main characteristics for the estimation of the potential impacts related to the energy facilities.

In Table 2 general data of the energy facilities included in the present scenario analysis are given.

It should be noted in Table 2 that power stations 1SPG and 4SPG are identical. In these power stations the generating units formed by a set of internal combustion engine – generator, are grouped in three cells. A simplify scheme for one cell is shown in Fig. 3.

In a cell, the fuel oil is fed to the internal combustion engines (ICEs) from the fuel treatment unit, where the fuel oil is preheated and centrifuged in order to reduce its viscosity and humidity. The heat used in the fuel treatment unit is recovered from the combustion gases through a heat recovering boiler. Combustion gases could be conveniently bypassed to follow heat demand. The electric power generated is transmitted from the generators to the electricity treatment unit, where the generators are synchronized and the power generation is regulated according to the effective

Table 3
Main typical operating parameters of the generating units.

Technology	Installed power (MW)	Typical load factor	Specific fuel consumption (g/kW h)	Hourly fuel consumption (kg/h)	Efficiency (%)
ICE-HFO	1.7	0.85	210	303.45	41.6
ICE-DO	1.8	0.75	225	303.75	37.4

Table 5
Results of combustion gases analysis in the generating units operating at typical load factor.

Technology	T_{mean} (°C)	T_g (°C)	O_2 (%)	CO (ppm)	NO (ppm)	NO_2 (ppm)	SO_2 (ppm)	CO_2 (%)	λ
ICE-HFO	32 [0.82]	250 [1.25]	13.3 [0.07]	750 [20.02]	901 [8.03]	10 [0.92]	369 [2.72]	6 [0.05]	2.6 [0.03]
ICE-DO	31.7 [0.95]	472.5 [0.91]	9.8 [0.09]	478 [6.53]	785 [5.67]	10 [0.82]	75 [1.26]	8.2 [0.07]	1.8 [0.02]

[ ] Standard deviation, the given values are the average for 10 replicates.

Table 6
Emission factor for the specified species.

Technology	CO (g/kg$_f$)	SO_2 (g/kg$_f$)	NO_{2eq} (g/kg$_f$)	PM_{10}[a] (g/kg$_f$)	CO_2 (kg/kg$_f$)
ICE-HFO	24	27	12.8	5.28	3.06
ICE-DO	12	4	8.4	1.95	3.13

[a] *Source*: EPA [36].

energy demand. Finally the electricity is sent to the electric grid through the exit transformers.

Energy audits were performed to determine facilities characteristics and operating conditions, the results and data derived from these are given in Tables 3 and 4. Table 3 shows the parameters determined as typical for the generating units in operational stage. The magnitude of these parameters were established by measuring at power stations, and with data gotten from the facilities data base.

Observe in Table 3 that the efficiencies calculated for the generating units, with a value of 41.7% and 37.4%, are close to the upper limit for these technologies.

Once the typical operating parameters for the generating unit are established, the main characteristics of the power stations can be defined. These are given in Table 4.

In Table 4 the operating hours are expressed in (h_{motor}/yr), this is calculated summing the annual operating hour of each generating unit installed at power stations.

The term *raw energy consumption* refers to the amount of energy converted in an energy facility or group of them from the raw form to another final useful form of energy, e.g. the fuel oil converted into electricity by the generating units.

The term *effective energy demand* refers to the amount of energy demanded by the user system in its final form, e.g. electricity demanded by the electric grid from the power stations.

3.3. Emissions inventory and accomplishment of the regulatory emissions standard

The emission inventory is a corner stone to perform an IAES. In this survey, an emission inventory with high spatial and temporal resolution was made. The included polluting gases are those established by the Cuban standard NC 111: 2004 [36] as main polluting agents. In this way the emissions of PM_{10}, SO_2, NO_x and CO were monitored.

To assess the contribution to global warning the CO_2 emissions were inventoried.

Table 7
Annual emission inventory.

Power station	CO_{2eq} (ton)	SO_2 (ton)	CO (ton)	NO_{2eq} (ton)	PM_{10} (ton)
4SPG	47,708	409	363	187	79
1SPG	27,115	232	206	106	45
2SPG	17,085	22	62	44	10
3SPG	8542	11	31	22	5
All	100,451	674	662	360	139

Table 8
Accomplishment of the Cuban standard for emissions regulation NC-TS 803: 2010.

Technology	Emissions (mg/Nm^3)[a]		
	SO_2	NO_x	PM_{10}
ICE-HFO	813	946	155
Maximum allowable emission	2500	2000	160
ICE-DO	113	569	53
Maximum allowable emission	1000	2000	80

[a] Reference conditions 273.15 K, 101.325 kPa, dry gases, O_2 ref. 15%.

The emission inventory is based on emission factors for the specific species and the fuel rate consumption. For the pollutants SO_2, NO_2, and CO the emission factors were determined based on combustion gases analysis. The emission factor for CO_2 is based on the carbon content of the fuel, the conversion efficiency of carbon (C) into CO_2, and the molar mass ratio CO_2/C. Carbon conversion efficiency has been established based on combustion reaction modeling. The emission factors for PM_{10} were taken from FIRE (Factor Information Retrieval Data System), which is a database containing EPA's estimated emission factors for hazardous and criteria air pollutants [37].

The combustion analysis was performed according to the standards established by EPA [38], and adopted by the Cuban standard to regulate the maximum allowable emission of pollutants to the atmosphere in punctual fixed sources as in the case of generating facilities of electricity and steam [39]. Those methods are: the 6C for SO_2, and for NO_2 and CO the methods 7E and 10 respectively. Combustion analysis results are presented in Table 5. These results allowed modeling combustion reactions and calculate all related parameters.

The emission factors established for this survey are given in Table 6.

In Table 6 it is observed that nitrogen oxides ($NO_x = NO + NO_2$) is expressed as NO_{2eq}, in this way it has been assumed that 25% of NO is transformed into NO_2 by direct chemical oxidation when it is released into the atmosphere, so $NO_{2eq} = NO_2 + 0.25NO \cdot M_{NO_2}/M_{NO}$. This assumption is based on the observation that once emitted, NO can be transformed into NO_2 by direct chemical oxidation. However, at low concentrations this reaction is slow, and less than 25% of NO is converted [40].

Based on the emissions factors given above, and the annual fuel consumption, the annual emissions inventories shown in Table 7 were completed.

3.3.1. Accomplishment of the regulatory Cuban emissions standard

In Cuba, gaseous emissions are regulated by the Standard TS 803:2010, which will be applied on a trial phase throughout the national territory till 2013, when it should be updated. This standard establishes the maximum allowable emissions from electricity and steam generating facilities in order to protect the human health and the environment [39].

According to the standard, the maximum allowable emissions should not be exceeded in the operational stage, and it must be taken into account for planning new energy facilities. Exceptionally the values for the maximum allowable emissions may be lower than those settled in the standard. These more stringent values can be established by the environmental regulatory authority based on onsite environmental impacts assessment.

Table 8 shows the maximum allowable emissions and the values determined in operating stage for the facilities included in this study. These values were measured and expressed at reference condition according to the method established in the referred standard. The PM_{10} was adopted from EPA [37] in g/kg$_f$ (as shows Table 6), and expressed in the units referred in the standard based on the fuel consumption and gas volume generated in the combustion reaction at reference condition.

Table 8 shows that the emission values determined do not exceed in any case the limit settled in the standard. However, to assess the impact of energy generation on air quality and its consequences on human health, pollutants dispersion modeling is needed.

3.4. Pollutants dispersion modeling

Generally for most air pollutants other than the globally dispersing greenhouse gases, atmospheric dispersion is significant over hundreds to thousands of km, due to important effects not negligible at local scale neither regional [3]. However the dispersion of pollutants chemically stable in the region of the emission can be predicted using a Gaussian plume model. These models assume that pollutant emissions are carried in a straight line by the wind, mixing with the surrounding air in all directions, horizontally and vertically, to produce pollutant concentrations with a normal (or Gaussian) spatial distribution [41]. The use of these models is typically constrained to a distance of 100 km from the source. In this survey, as the scope is local, a Gaussian plume model has been adopted. This allows assessing the increment in pollutant concentration related to point sources of emissions, such as power and heat generating plants. The software adopted is the ISC-AERMOD View [42].

The local dispersion was modeled with ISCST3 Dispersion Models, using complex terrain, concentration and regulatory options. The modeling was carried out in a domain of 6×5.6 km, shown in Fig. 2. A uniform Cartesian grid of receptors with a resolution of 100×100 m has been used. The required information concerning energy facilities is given in Tables 9 and 10.

Typical emission parameters for the technologies included in the present analysis are given in Table 9. These values are referred to one generating unit.

In the stations 1SPG and 4SPG, because four generating units are connected to one stack (forming a cell), the emission rate and exit gases velocity per stack, depend mainly on the number of generating units in operation per cell. This relation is shown in Table 10.

For facilities 2SPG and 3SPG, because each generating unit has its own stack, the emission rate and gas exit velocity per stack correspond with those given for one generating unit.

Besides the emission parameters, the hourly variations of the gases release parameters during the survey period are considered.

For facilities 1SPG and 4SPG, due to the variability of the emission over the time, it was necessary to build hourly emissions files for NO_{2eq}, SO_2, CO and PM_{10}. The emission files include the hourly variation per stack of the emission rate, temperature, and gas exit velocity. Table 11 shows all possible operational arrangement to satisfy an effective energy demand of 10 MW, and its influence in the emissions parameters. The set in italic cause the lowest local impacts in terms of exposure to polluting gases and impacts on health.

Table 10
Variation of stack emissions parameters according to generating units in operation.

Emission parameters	Generating units in operation			
	1	2	3	4
Gases exit velocity (m/s)	5.61	11.21	16.82	22.43
NO_{2eq} emission rate (g/s)	1.77	3.54	5.31	7.08
SO_2 emission rate (g/s)	2.31	4.62	6.94	9.25
CO emission rate (g/s)	2.05	4.11	6.16	8.21
PM_{10} emission rate (g/s)	0.44	0.89	1.33	1.78

Daily systematic emissions patterns were found for facilities 2SPG and 3SPG. In that case the emission rate variation for each stack can be appropriately described by 24 h Emissions Rate Factor (ERF). ERF is a multiplier in the range of 0–1 of the emission rate specified for the source, e.g. a factor of 0 means that the source is not emitting, a factor of 0.5 means that the source is emitting 50% of the specified emission rate.

From the point of view of health impact assessment, results from modeling on annual average concentration increments are the relevant ones, but for impact on air quality assessment modeling results for 24 h averaging time were also obtained.

3.5. Perturbation analysis for impact reduction

An important part in this study is the analysis of perturbations in the base scenario that could potentially reduce the environmental impacts for a given effective energy demand. In this way it could be assessed perturbations concerning source location, conversion efficiency, end of pipe emission control, technology, and operating arrangement. In this study it has been acknowledged that source location is basically modifiable in the design stage, because in the operating stage it will require important investments. On the other hand, the efficiencies calculated for power facilities are in the typical range for the installed technology, so, improving conversion efficiency will require big efforts, and resulting impact reduction could be negligible. End of pipe emission control has not been included in the analysis because they were considered unaffordable investments in the short term.

In this study basic low investment perturbations in technology and operating arrangement are assessed. In this way it has been assessed to modify stack height as it is shown in Table 9. This action is included in the short term investments plan for facilities under assessment.

For perturbation analysis in operating arrangements, were analyzed which arrangement for a specific effective energy demand the minimum local impact.

Table 9
Emission parameters for gases dispersion modeling by technology.

Technology	Stack height[a] (m)			Stack diameter (m)	Velocity[b] (m/s)	Temperature (K)	Emission rate[b] (g/s)			
	BL	A	B				SO_2	CO	NO_{2eq}	PM_{10}
ICE-HFO	12	12	24	1.02	5.6	523.2	2.31	2.05	1.06	0.44
ICE-DO	4.4	7	7	0.45	31	745.7	0.35	0.98	0.69	0.16

[a] Stack height is given for the three scenarios BL: base line scenario, scenario A, and scenario B.
[b] The values for the velocity and emissions rate given in this table are those representatives for one generating unit, for ICE-HFO this values depend of the operating unit per cell, the variation of this values are contained in the hourly emission file used for modeling.

Table 11
Possible operating arrangements, related emissions parameters, and SO_2 marginal exposure.

EED (MW)	Generating units in operation required	Operating units per cell			Gas exit velocity (m/s)			SO_2 emission rate (g/s)			SO_2 marginal exposure (μg/m^3 inhabitant/MW h)
10	7	4	3	0	22.4	16.8	0	9.24	6.93	0	2.71
		4	2	1	22.4	11.2	5.6	9.24	4.62	2.31	3.15
		3	3	1	16.8	16.8	5.6	6.93	6.93	2.31	3.23
		3	2	2	16.8	11.2	11.2	6.93	4.62	4.62	3.36
cells →		1	2	3	1	2	3	1	2	3	Power station

For perturbation analysis in operating arrangements, alternatives leading to the minimum local impact when meeting the same effective energy demand were analyzed. This was analyzed for the stations 1SPG and 4SPG, because of the influence of the operating arrangements in emission parameters, as shown in Table 10. The influence of the operating arrangement is related to gas flow and velocity variations by a factor from 1 to 4 depending on the number of units running in parallel at one cell. So, for example, when the effective energy demanded is 4.3 MW three units in operation are required. Three alternative operating arrangements are possible for meeting this demand: (1) to run one unit from each cell, (2) to run three units at one cell, and (3) to run two units at one cell and one at another cell. In each alternative the total emission will be equal, but stack emission parameters will differ. The alternative 1 leads to the lowest gas flow, emission rates, and gas exit velocity per stack so worsening pollutant dispersion, and rising ground level concentration. Because in alternative 2, gas flow, emission rate, and gas exit velocity through the stack have the highest value, favoring the pollutants dispersion and decreasing ground level concentrations.

A similar analysis for all alternatives was performed, determining in each case the marginal exposure to SO_2 as function of the operating arrangement. See the example shown in Table 11 for an operating arrangement where 7 units in operation are required. The marginal exposure to SO_2 is adopted as indicator, instead of the total exposure because making an analysis for a single technology in similar operating condition, the pollutant emissions are correlated. So, no different result will be reached including all pollutants, only a higher modeling effort. The marginal exposure is calculated according to Eq. (8). The operating arrangements leading to the lowest exposure were then established. The set in italic in Table 11 causes the lowest local impacts in terms of exposure, and consequently the lowest health impact. The arrangements causing the lowest impacts were established by modeling the dispersion for all possible arrangements which are summarized in Table 12. Thirty operational arrangements were modeled.

In the example in Table 11 there are always running 7 generating units, but again looking at these power plants configuration, (Fig. 3) there are different alternatives of operating arrangement to meet the same energy demand. E.g. in Table 11 (column 3) the operating units per cell, needed to meet 10 MW, are shown. For each alternative the total emission will be equal, but stacks emission parameters will differ, see variation in velocity and emission rates. The variation in these parameters will generate different pollutant dispersion patterns and as a consequence different impacts. The first row in Table 11 is the optimal situation. because the gas exit velocity under this arrangement favors the dispersion, and the resulting ground level concentrations, despite similar net emissions, is lower in comparison to the other arrangements.

Table 12
Operational arrangements at station 1SPG and 4SPG in scenario A and B.

Generating units in operation required	Operating arrangements (operating units per cell)		
	Cell 1	Cell 2	Cell 3
2	2	0	0
3	3	0	0
4	4	0	0
5	4	1	0
6	4	2	0
7	4	3	0
8	4	4	0
9	4	4	1
10	4	4	2

Finally three scenarios were studied. Base line scenario represents real life operating stage. Scenario A is induced by modifying the stack height at stations 2SPG and 3SPG, as shows Table 9, and from modifications in operating arrangements. Scenario B is derived from stack height modification in all station, and modifications in operating arrangements.

4. Results and discussion

Efficiencies determined for ICE-HFO and ICE-DO technologies was 41.7% and 37.4% respectively, these values are typical for these technologies, indicating a good maintenance routine and operating regimes.

The ranking of the facilities from the largest to the smallest, according to the annual operating hours, raw energy consumption, effective energy demand, and emissions is the following: 1st – 4SPG, 2nd – 1SPG, 3rd – 2SPG, and 4th – 3SPG. The stations with a higher exploitation regime are those located in the areas where the population density is low (see Fig. 2), which was a logic operational decision in order to reduce the population exposure to polluting gases.

Apart from CO_2 emissions, the highest emissions in the second and third place correspond to SO_2 from ICE-HFO technology and NO_{2eq} from ICE-DO technology respectively. In total SO_2 emissions are higher than NO_{2eq} emissions by two fold. This is related to high sulfur contents in the HFO.

From combustion gas analysis was concluded that, in all cases the maximum allowable emissions established in the Cuban standard are meet. However, the impact on air quality conditions and human health, on the adjacent highly populated areas require a deeper and detailed analysis.

Fig. 4 shows the modeling results for SO_2 emissions in the baseline scenario, and the related impact in air quality conditions. SO_2 has been adopted as reference for air quality analysis, because it was demonstrated to be the main causal agent of air quality deterioration.

In Fig. 4a the maximum value in the color scale corresponds to the Maximum Allowable annual average Concentration (MAC) established by EPA in the national ambient air quality standards for USA [43]. This is done with the purpose of recognizing the areas where the MAC is exceeded. This value has been adopted from EPA standards in view that the Cuban standard NC 39: 1999 [44] do not regulate the annual average MAC, even though for health impact assessment annual average concentration is relevant. Note that in the whole area the incremental calculated concentrations do

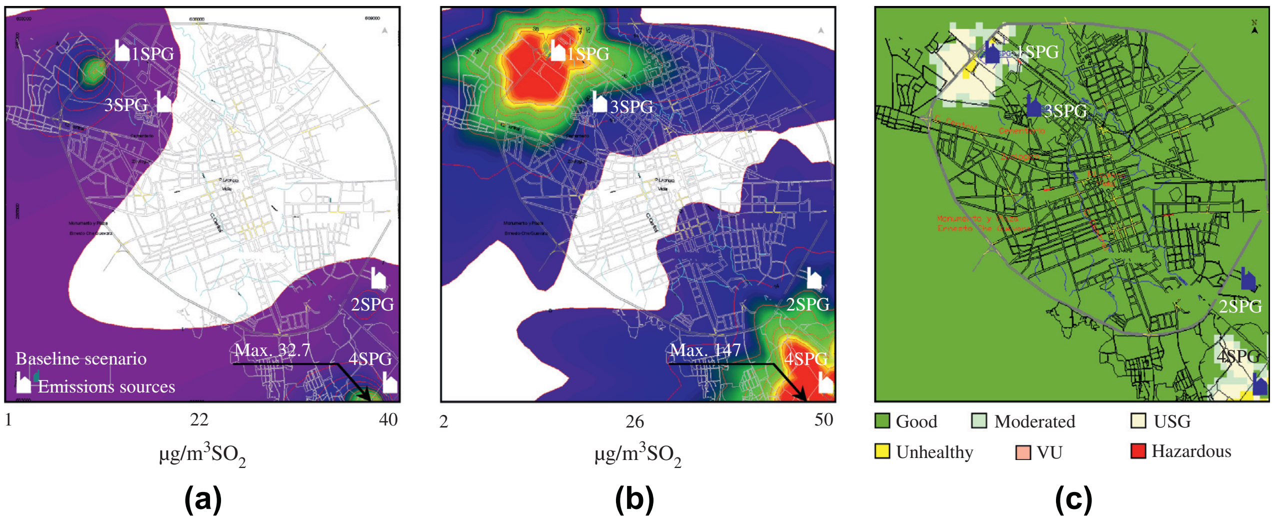

Fig. 4. Impact on air pollution related to SO_2 emissions from power stations in the baseline scenario: (a) Incremental annual average concentration, (b) incremental higher concentration for 24 h averaging time, and (c) impact on air quality condition according to NC 111: 2004.

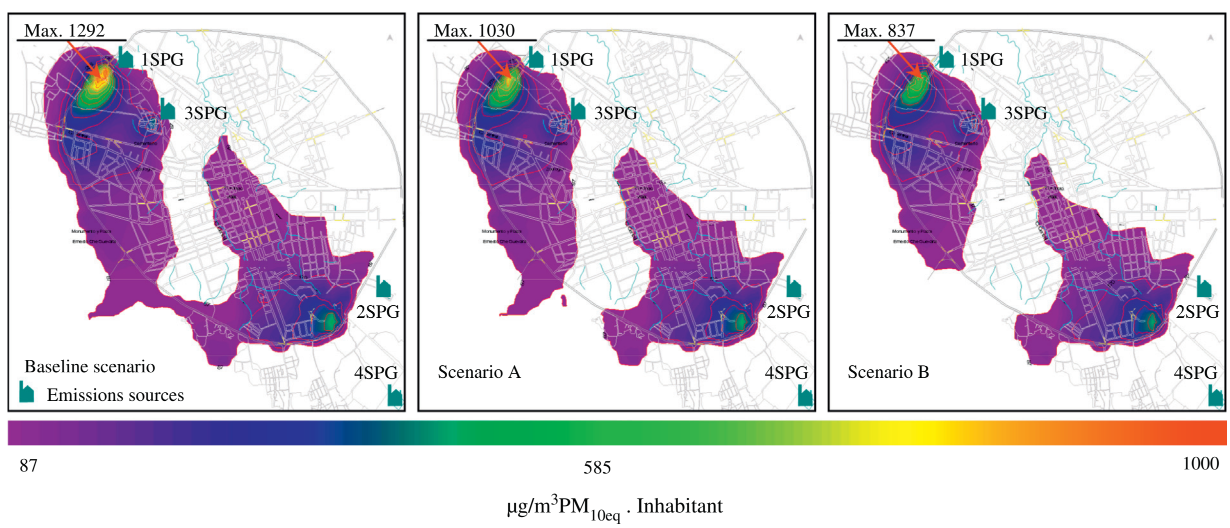

Fig. 5. Annual exposure maps generated for different scenarios.

not reach the MAC. However in some areas, even a relatively low value of the background concentration, could lead to a total concentration higher than the MAC.

In Fig. 4b, the maximum value in the color scale, corresponds to the MAC for 24 h averaging time established in the Cuban standard NC 39: 1999 [44], this map represents the worst scenario for a 24 h average concentration period. The incremental concentration calculated exceeded the MAC in red areas. The percentile analysis for the two receptors with the highest calculated incremental concentration revealed that in the southeast receptor the incremental concentration exceeds the MAC 65 days in the year, and in the northwest 57 days. Fig. 4c shows the impact on air quality deterioration of the scenario presented in Fig. 4b where, even without considering the background concentration, the air quality condition is unhealthy in some small areas.

Fig. 5 shows how the incremental exposure level goes down from the baseline scenario to the scenario B, the highest exposure level decreases in 35%. These maps allow identifying the northwest area as the most affected. This area is not where the incremental concentrations are higher; however the high population density influenced the results.

Fig. 6 shows that station 1SPG generates approximately 3 times the marginal exposure generated by 4SPG, despite station 4SPG emits 1.8 times the amount of pollutant emitted at 1SPG. According to this indicator it can be established which station should be operated at higher power rate in order to reduce the population exposure to polluting gases. The same figure also shows how the exposure generated by the station 1SPG could be reduced by 20% approximately from the base line scenario when operating arrangement are optimized and the stack height are increased.

Fig. 6 shows the impact on health in years of life potential lost per year for each specific facility. The differences occur because of the different operating regimes, the technologies, and location. These differences are captured when Eqs. (2) and (8) are applied. For each specific plant the incremental concentration caused in the study domain is calculated. The matrix of incremental concentration for each specific plant is different due to different emission parameters. The population that they affect due to its location is also different. So when the equations are applied to each specific plant the calculated impacts differ. This is illustrated above, combining figures, graph and data. The marginal exposure is an index designed to capture the location effect (Eq. (8)), see e.g. how the

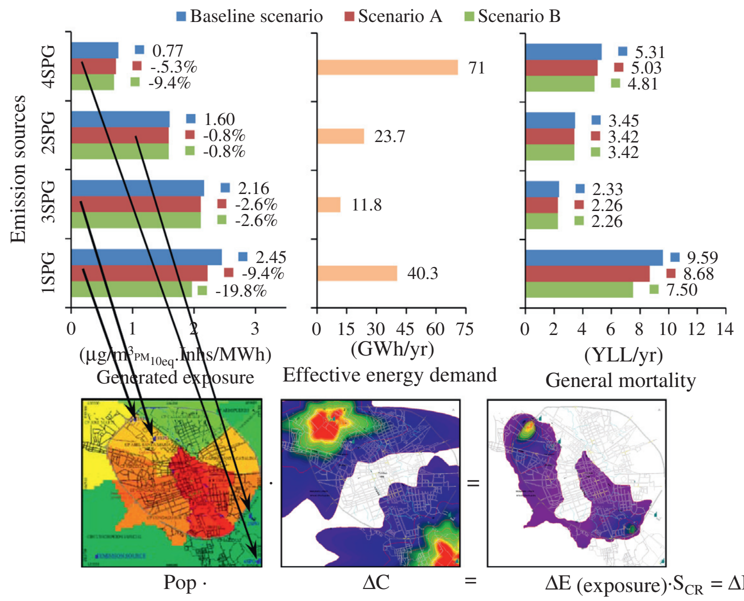

Fig. 6. Annual exposure and related impact on health expressed as years of life potentially lost, relation with the location and effective energy demand.

plant 1SPG located in the most densely populated area generate the higher value for this indicator. The total impact (Eq. (2)) it is not expressed in marginal terms, so it captures all effects, location and operating regimes which are the cause of different emissions parameters. Consequently the plant 3SPG generates a high exposure per MW h, due to its location in a place where downwind population is high; however it meets the lowest effective energy demand thus generating the lowest impact. The greatest impacts are generated by the stations 4SPG and 1SPG, mainly due to the required exploitation regimes to meet the effective energy demand. The general mortality from baseline scenario to scenario B can be reduced in 13% approximately. The highest reduction is achieved in the station 1SPG with a value about 20%.

Finally the contribution to CO_2 is entwined to the raw energy consumption. On this regard, as the operating efficiencies are in the typical range for the installed technologies, and the effective energy demand is considered constant, no mitigation opportunities were identified. The ranking of facilities according to CO_2 emissions correspond with the ranking established based on the raw energy consumption.

5. Conclusions

Recently, social concern due to environmental impact of energy conversion, and the awareness that it must be internalized has led to the establishment of environmental criteria, to be considered in decision-making processes.

In this work chronic mortality due to PM_{10} exposure has been adopted as health impact indicator. It is expressed in years of life potentially lost per year. To distinguish the exposure level to mixtures constituted by different proportions of pollutants a total exposure indicator has been established. This includes all pollutants expressed as PM_{10} equivalent. A map of total incremental exposure has been developed and adopted to elucidate the exposure pattern in the study domain, which is also a signal to prioritize mitigation actions.

The marginal exposure generated by each specific facility is settled as indicator to assess the location effect on the impact generated.

This survey demonstrate that it is possible to have an appropriate representation of the impacts related to energy use at local scale in terms of air quality, exposure generated to polluting gases and health damage, despite some data were necessarily adopted from the specialized literature. As shows the case study presented here.

The methodology developed allows, besides diagnose a given scenario, a perturbations analysis on several variables inherent to energy facilities in order to improve their environmental performance. In the present case-study the perturbations analysis allowed identify an impact reduction on health about 13%.

Economic limitations in developing countries hamper air quality and energy management. The cost of diagnosis equipment and actions to improve the environmental performance of energy technologies are not always affordable. The population is then exposed to high health risks. The external effects related to energy use are generally underrated in decision making. However this research shows that even some low investment actions can reduce health risk. In this way the modifications in the operating arrangement derived from this survey have been implemented in the energy facilities without cost. In addition, investments have been prioritized to raise the stacks height in the facilities causing the highest impacts. This way achieving increased performance in terms of environmental benefit of the scarce investments that can be devoted to this issue.

The results obtained in this study represent an important step forward in the assessment at local scale of the external effects of energy use. For first time in Cuba, in the decentralized power sector, this kind of assessment is made.

Acknowledgments

This work was supported by VLIR program through the project: Environmental education and development of clean technologies. It also was possible thanks to the collaboration between Vrije Universiteit Brussel and Universidad Central 'Marta Abreu' de Las Villas. The collaboration of the dependencies of the Ministry of Science Technology and Environment of Cuba in province of Villa Clara has been also valuable, as well as the cooperation of the enterprises involved.

References

[1] Cairncross EK, John J, Zunckel M. A novel air pollution index based on the relative risk of daily mortality associated with short-term exposure to common air pollutants. Atmos Environ 2007;41:8442–54.
[2] Linares P, Munoz L, Ramos A, Montes J. Internalisation of externalities into energy decision-making: a model for the social optimisation of the operation of power systems. In: 2nd Atlantic workshop on energy and environmental economics, Vigo; 2006.
[3] European Commission. EUR 21951 EN – ExternE – externalities of energy – methodology 2005 update. Luxembourg; 2005.
[4] Turtós Carbonell L, Meneses Ruiz E, Sánchez Gácita M, Rivero Oliva J, Díaz Rivero N. Assessment of the impacts on health due to the emissions of Cuban power plants that use fossil fuel oils with high content of sulfur. Estimation of external costs. Atmos Environ 2007;41:2202–13.
[5] Exxon Mobil. The outlook for energy: a view to 2030; 2010.
[6] Statistics National Office. Statistical yearbook of Cuba 2010. La Habana; 2010.
[7] Mahapatra D, Shukla P, Dhar S. External cost of coal based electricity generation: a tale of Ahmadabad city. Energy Policy 2012;49:253–65.
[8] Frangopoulos CA, Caralis YC. A method for taking into account environmental impacts in the economic evaluation of energy systems. Energy Convers Manage 1997;38:1751–63.
[9] Zvingilaite E. Human health-related externalities in energy system modelling the case of the Danish heat and power sector. Appl Energy 2011;88:535–44.
[10] Andersen MS, Sprenger R-U. Market-based instruments for environmental management: politics and institutions. UK: Edward Elgar Publishing; 2000.
[11] Tietenberg T, Folmer H. In: Oates WE, editor. The international yearbook of environmental and resource economics: a survey of current issues; 2003.
[12] Klöpffer W. The role of SETAC in the development of LCA. Int J LCA 2005:11.
[13] Bram S, De Ruyck J, Lavric D. Using biomass: a system perturbation analysis. Appl Energy 2008;86:194–201.
[14] Althaus H-J, Gabor Doka, Roberto Dones, Thomas Heck, Stefanie Hellweg, Roland Hischier, et al. Ecoinvent report no. 1. Overview and methodology. Dübendorf: Ecoinvent Centre; 2007.
[15] Wang X, Mauzerall DL. Evaluating impacts of air pollution in China on public health: implications for future air pollution and energy policies. Atmos Environ 2005.
[16] Cuesta O. Nueva política de calidad del aire y sus respectivos desarrollos normativos 2007–2010. III Taller Contaminación Atmosférica Vs Desarrollo Sostenible. La Habana, Cuba; 2008.
[17] Meteorological Center of Villa Clara. Emission source inventory, Santa Clara, 2011. Santa Clara, Cuba; 2011.
[18] WHO. Air quality guidelines global update 2005. Particulate matter, ozone, nitrogen dioxide and sulfur dioxide, 2nd ed. Copenhagen; 2005.
[19] Wilson R, Spengler JD. Particles in our air: concentrations and health effects. Harvard University Press; 1996.
[20] Holland M, Hunt A, Hurley F, Navrud SPW. Methodology for the cost-benefit analysis for CAFE: Overview of methodology. Technology environment, vol. 1. Didcot, UK: AEA; 2005.
[21] Daniels MJ, Dominici F, Samet JM, Zeger SL. Estimating particulate matter-mortality dose–response curves and threshold levels: an analysis of daily time-series for the 20 largest US cities. Am J Epidemiol 2000:152.
[22] Dominici F, Walter A. Rosenblith new investigator award, time series analysis of air pollution and mortality. A Statistical Review Health Effects Institute; 2004.
[23] Pope III CA, Burnett RT, Thun MJ, Calle EE, Krewski D, Ito K, et al. Lung cancer, cardiopulmonary mortality, and long-term exposure to fine particulate air pollution. J Am Med Assoc 2002;287:1132–41.
[24] Samoli E, Analitis A, Touloumi G, Schwartz J, Anderson HR, Sunyer J, et al. Investigating the dose–response relation between air pollution and total mortality in the APHEA-2 multicity project. Environ Health Perspect 2005;113: 88–95.
[25] Samet JM, Zeger SL, Dominici F, Curriero F, Coursac I, Dockery DW, et al. The national morbidity, mortality and air pollution study part II: morbidity and mortality from air pollution in the United States. Baltimore, Maryland: Health Effects Institute; 2000.
[26] Cizao R, Shilu T. Health effects of ambient air pollution – recent research development and contemporary methodological challenges. Environ Health 2008;7:56.
[27] Ostro B. Outdoor air pollution: assessing the environmental burden of disease at national and local levels. Environmental burden of disease. Geneva: World Health Organization; 2004.
[28] Municipality Statistics Office. Popular councils of Santa Clara city; 2010.
[29] Rabl A. Interpretation of air pollution mortality: number of deaths or years of life lost? J Air Waste Manage Assoc 2003;5:41–50.
[30] O'Neill M, Loomis D, Aburto VHB, Gold D, Hertz-Picciotto I, Castillejos M. Do associations between airborne particles and daily mortality in Mexico City differ by measurement method, region, or modeling strategy? J Expos Anal Environ Epidemiol 2004;14:429–39.
[31] Stieb DM, Judek S, Burnett RT. Meta-analysis of time-series studies of air pollution and mortality: effects of gases and particles and the influence of cause of death, age, and season. Air Waste Manage Assoc Ottawa, Canada 2002:470–84.
[32] Molina E, Meneses E. Evaluación epidemiológica del impacto de los contaminantes del aire en la salud. La Habana: Instituto Nacional de Higiene, Epidemiología y Microbiología (INHEM) & Centro de Gestión de la Información y Desarrollo de la Energía (CUBAENERGIA); 2005.
[33] CITMA, PNUMA, UN-HABITAT, Agenda 21 Nacional, IPF. Perspectivas del medio ambiente urbano: GEO Santa Clara. La Habana, Cuba: Editorial academia; 2007.
[34] Ministry for the Environment. Good practice guide for atmospheric dispersion modelling. Wellington, New Zealand: National Institute of Water and, Atmospheric Research; 2004.
[35] Meteorological Center of Villa Clara. Hourly meteorological data file. Santa Clara, Cuba; 2010.
[36] Cuban National Bureau of Standards. NC 111: 2004. Air quality – rules for the observation of air quality in human establishments; 2004.
[37] EPA. Factor Information REtrieval (FIRE) Software. Technology transfer network clearinghouse for inventories & emissions factors; 2004.
[38] EPA. Test methods and performance specifications. Technology Transfer Network, Emission Measurement Center; 2008.
[39] Cuban National Bureau of Standards. NC TS 803: 2010. Air quality – admissible maximum emissions of pollutants to the atmosphere in punctual fixed sources of generating facilities of electricity and steam; 2010.
[40] Stranger M. Characterization of health related particulate and gas phase compounds in multiple indoor and outdoor sites in Flanders [PhD]. Belgium: University of Antwerp; 2005.
[41] European Commission. Maintenance, improvement, extension and application of the EXTERNE accounting framework. European Commission; 1997.
[42] EPA. ISC-AERMOD view help. Lakes Environmental Software; 2000.
[43] EPA. National Ambient Air Quality Standards (NAAQS); 2012.
[44] Cuban National Bureau of Standards. NC 39: 1999. Air quality – health and sanitary requirements; 1999.