Environ Sci Pollut Res (2016) 23:20922–20936
DOI 10.1007/s11356-016-7258-0

RESEARCH ARTICLE

The assessment of health impacts and external costs of natural gas-fired power plant of Qom

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Received: 27 February 2016 / Accepted: 14 July 2016 / Published online: 3 August 2016

Abstract The external health damage costs of the combined cycle natural gas-fired power plant of Qom were investigated via the simplified impact pathway approach. Emitted particulate matter (PM_{10}) and gaseous pollutants (NO_x, CO, and SO_2) from the power plant stack were measured The health effects and related costs were estimated by QUERI model from AirPacts according to the emissions, source and stack parameters, pollutant depletion velocities, exposure-response functions, local and regional population density, and detailed meteorological data. The results showed that the main health effect was assigned to the nitrate as restricted activity days (RAD) with 25,240 days/year. For all pollutants, the maximum health damage costs were related to the long-term mortality (49 %), restricted activity days (27 %), and chronic bronchitis (21 %). The annual health damage costs were approximately 4.76 million US$, with the cost being 0.096 US per kWh of generating electricity. Although the health damage costs of gas-fired power plant were lower than those of other heavy fuels, it seems essential to consider the health and environmental damages and focus on the emission control strategies, particularly in site selection for the new power plants and expanding the current ones.

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Keywords Power plant · Natural gas · Health damage costs · QUERI model

Introduction

Electricity is a key factor in social development. Given the rapid growth of economy, population and technology, electricity consumption is increasingly on the rise whether in developed countries or in developing countries. Power plants are industries that produce electricity (Jeong et al. 2008; Kumar and Goyal 2014). However, energy production can affect the environment and health. Its most important effect on human health can occur through air pollution (i.e., long or short-term exposure to particulate matter (PM), nitrogen oxides (NO_x), sulfur dioxide (SO_2), etc.) such as mortality and morbidity increasing and reducing life expectancy (Hainoun et al. 2010).

Thermal power plants are one of the main artificial sources of producing toxic gases and particulate matter. Apart from technological improvements, the efficiency of thermal power plants is still low; occurring in the range of 50 % to 70 %, and thus, the fuel energy is often wasted as heat (Athar et al. 2013). Numerous studies worldwide have proven the health and environmental risks and adverse effects related to air pollutants emitted by thermal power generation plants (Garg et al. 2001; Gillani et al. 1998; Islas et al. 2002; Smith et al. 2000). Air pollutants emitted by power plants can affect local air quality and global environmental impacts, including the increase of greenhouse effects (Jeong et al. 2008).

Fossil fuel power plants cause the emission of pollutants such as NO_x, SO_x, CO_2, CO, PM, organic gases, and polycyclic aromatic hydrocarbons. The use of natural gas in power plants can reduce such emissions. However, natural gas fuel significantly causes CO_2 and NO_x emissions (Jaramillo et al. 2007; Shao et al. 1995) as well as methane emissions, PM,

SO_x, CO, formaldehyde, ammonia (NH_3), and non-methane hydrocarbons (NMHCs) (Lee et al. 2013; Spath and Mann 2000).

NO_x and SO_2 are gaseous pollutants that aggravate asthma and respiratory complications (Amster et al. 2014). Studies have shown that exposure to NO_x is associated with increased frequency of respiratory complications (van Strien et al. 2004; Zhao et al. 2008), increased susceptibility to respiratory infections (Brauer et al. 2002; Chen et al. 2007), increased respiratory symptoms leading to hospitalization (Barnett et al. 2005; Iskandar et al. 2011; Tramuto et al. 2011) and increased mortality rates (Heinrich et al. 2012; Moolgavkar et al. 2013). NO_x also involves in the creation of urban smog (Tang and Mudd 2015). Previous studies have indicated that exposure to SO_2 is associated with the overall increased mortality rate caused by respiratory problems (Chen et al. 2012), exacerbation of existing respiratory disease (Chen et al. 2007), increased risk of asthma (Clark et al. 2010) and increased prevalence of respiratory symptoms such as wheezing and dyspnea (Chen et al. 2007), and is one of the most important factors in the occurrence of acid rain (Tang and Mudd 2015).

PM is a complex mixture of particles or droplets that may include chemicals, acids, organic materials, metals, soil or dust (Anderson et al. 2012). Previous epidemiological studies indicate that air pollution caused by PM leads to about 3 million premature deaths per year (Lelieveld et al. 2015). Particles with an aerodynamic diameter less than 10 μm (PM_{10}) are among the major air pollutants that have a detrimental effect on human health (Kassomenos et al. 2013). PM can cause cardiovascular, cerebrovascular, respiratory diseases and oxidative stress in humans (Anderson et al. 2012; Canova et al. 2014). Several studies have been done on the effects of PM on human health, including short-term and long-term effects of PM_{10} on lung function, acute respiratory symptoms, asthma and COPD (chronic obstructive pulmonary disease) exacerbation, endothelial function, hospital admission, sperm quality, blood pressure, infant mortality, premature birth, birth weight, pro inflammatory mediators, coagulation blood markers, etc. (Brunekreef and Holgate 2002; Rückerl et al. 2011).

Atmospheric exposure to carbon monoxide (CO) also adversely affects the health. CO through binding to hemoglobin reduces oxygen availability and causes disturbances in function of organs such as heart and brain (which are sensitive to oxygen) (Kampa and Castanas 2008), including myocardial infarction (Bernstein et al. 2004). In long-term exposures, CO can cause disorders such as slow reflexes, confusion (Kampa and Castanas 2008), sleep disturbances, emotional distress, chronic fatigue, parenthesis, vertigo, memory deficits, polycythemia, difficulty working, neuropathy, recurrent infections, abdominal pain and diarrhea (Weaver 2009). Studies have shown that for every increase of 1 ppm of CO, heart failure hospitalizations or mortality rate are increased by 3.25 % (Shah et al. 2013).

Carbon dioxide (CO_2) does not directly affect human health in emission concentrations and after mixing in the open air, and is not considered a classical air pollutant (Jacobson 2008). However, it is seriously considered a greenhouse gas (GHG) leading to climate change and global warming (Montzka et al. 2011; Shakun et al. 2012; Solomon et al. 2009; Tang and Mudd 2015).

Environmental and health impacts of electricity generation are of particular concern due to high interaction of this energy sector with the environment. One of the widely used methods to assess the health and environmental effects of the energy sector and estimate the damage costs on the society is the impact pathway approach (IPA) that has been developed based on ExternE project (supported by the European Commission). The method was first introduced in 1997 to estimate the environmental costs such as air pollution, noise pollution and climate changes (Hainoun et al. 2010). The efficiency of this approach allowed its use in the power plants of some different parts of the world such as Mexico (Macías and Islas 2010), Cuba (Casas-Ledon et al. 2014; Turtós Carbonell et al. 2007), Indonesia (Liun et al. 2007), Turkey (Büke and Köne 2011), and Syria (Hainoun et al. 2010).

Iran is one of the few countries in the world that benefits from abundant initial energy resources including oil and gas. Thus, most of the country's power plants are based on fossil fuels such as gas, diesel, and heavy oil. Gas has the largest share; heavy oil and diesel are, respectively, used more in power plants. The natural gas used in Iran's thermal power plants has a calorific value about 55 MJ kg^{-1} with low sulfur level (Nazari et al. 2010). According to the statistics provided by Iran Grid Management Company, the gas-fired power plants have the highest share in electricity production (over 35 %). The combined cycle power plants, the steam power plants and hydroelectric power plants are in the next rankings (IGMC 2014). Natural gas is also considered one of the most important sources of energy in the world in domestic, commercial and industrial sectors (Jaramillo et al. 2007). Considering the high proportion of gas power plants in electricity production in Iran, and lack of research on health damage cost in Iran's gas power plants, this study aims at investigating the health effects and related damage costs caused by the emissions of NO_x, CO, SO_2, and PM_{10} of one of the natural gas combined-cycle power plants by the impact pathway approach (IPA). In this research QUERI version (the most detailed one) from AirPacts model developed by International Atomic Energy Agency (IAEA) has been used for estimating the health effect and damage cost.

Experimental methods

Study area and case description

The combined-cycle power plant of Qom is located at 15 km southwest of the city of Qom and almost in the center of Qom province. The area of Qom province is 11,526.262 square meters with a population of 1,151,672, according to the last national census (2011) and is located in an arid and semi-arid area. According to data from the weather station located in the plant, the annual average temperature (September 2013 to 2014) in the area was about 19 °C, and the prevailing wind is blowing from the West.

The plant altitude is 1049 m above sea level and is located at 34° 34′ 42 N and 50° 45′ 17 E. The plant has a production capacity of 714 MW, including four gas (128.5 MW) units and two combined cycle (100 MW) units, and its main fuel is natural gas.

Sampling and emission factor calculation

The plant has four gas generators for producing electricity and four chimneys with a diameter of 6 m and height of 55 m. Sampling and measuring the particulate and gaseous emissions of the plant have been done during different seasons. The ISOSTACK BASIC made by TCR-TECORA Company (Italy) was used for sampling the output particles of the plant stacks. The samplings were performed under isokinetic conditions during 20 min and at least two repeats. To establish isokinetic conditions, the velocity of the exhaust flue gas was measured, and according to the sampler nozzle diameter, the flow rate was selected which is required for achieving the sampling velocity equaling the flue gas velocity.

The measurement of gaseous pollutants (NO_x, CO, and SO_2) of the stacks as well as the temperature and pressure of stacks was done by using the direct reading Testo-350-XL device.

The gaseous pollutants (NO_x, CO, and SO_2) were measured as volumetric concentration (ppm) with online stack analyzer. Therefore emission factors were calculated according to the molar weight of each gas, pressure, temperature, flow rate of exhaust gas, and the amount of electricity produced by the power plant. The diagram of emission rate calculation method is shown in Fig. 1. Since PM_{10} was measured as $\mu g/m^3$, the emission rate of that was calculated according to the flow rate of exhaust gas and the amount of electricity produced.

Health effects and costs assessment

The impact pathways approach (IPA) is used to estimate the health effects and external costs attributed to air pollution emitted from the power plant. This method has been proposed in the ExternE project supported by the Europe Union (Bickel and Friedrich 2005; Hainoun et al. 2010). The IPA has been introduced in some sources as the impact pathway methodology (IPM) and damage function approach (DFA) (Büke and Köne 2011; Casas-Ledon et al. 2014; Markandya et al. 2002). The methodology of evaluation steps of this approach can be categorized briefly as follows (Fig. 2):

1. Determining and estimating data on the pollution source and its characteristics, including pollutants emission rate and depletion velocity, stack height and diameter, flow gas temperature and velocity, and source location parameters.
2. Estimating the distribution of pollutants emitted by power plants in the surrounding areas using the Gaussian distribution models at local distances (less than 50 km). In further distances and regional levels, the Eulerian or Lagrangian models such as wind rose trajectory model are used.
3. Estimating the health effects caused by exposure to the primary pollutants (including NO_x, SO_x, CO, and PM_{10}) and secondary pollutants (including nitrate and sulfate aerosols) emitted by the power plant using exposure-response functions (ERF).
4. Calculating the external costs associated with estimated health effects

Description of AirPacts model

In the present study a simplified solution was used to estimate the environmental impacts of energy production as SimPacts model developed by the IAEA (International Atomic Energy Agency). This model has been developed for use in developing countries based on EcoSense method used in the ExternE project (Hainoun et al. 2010; Krewitt et al. 1995; Spadaro 2002b). In the SimPacts model, the assessment of health

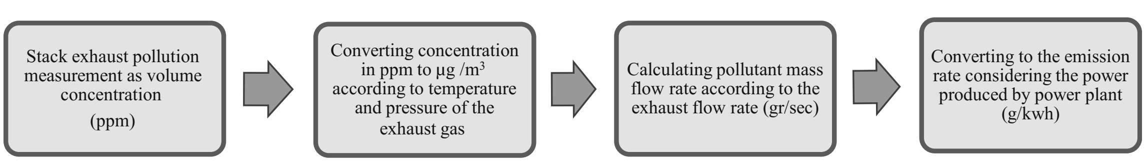

Fig. 1 Computation stages for pollutant emission factors

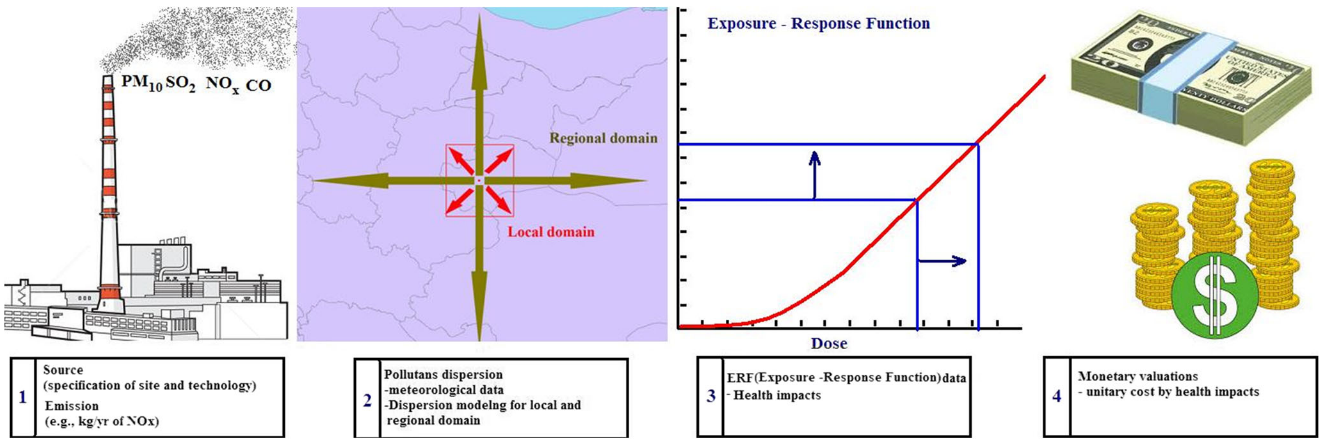

Fig. 2 The main steps of an impact pathway analysis

effects of air pollutants are known as AirPacts and divided into different versions depending on the available data, including SUWM, RUWM, and QUERI models (Spadaro 2002a). The SUWM (Simple Uniform World Model) model is the simplest one, which requires the minimum input data for the calculation of health effects. The RUWM model (Robust Uniform World Model) and QUERI (QUick Estimation of Respiratory health Impacts) model have been designed to calculate the effects more accurately and include detailed information from the pollutant source, weather conditions and the receptor. In this study, the QUERI model has been used which is the most advanced version of the RUWM model and estimates the health effects more accurately. In QUERI model, in addition to the detailed information on source and stack parameters, emission rate, depletion velocity and ERF, the partial hourly meteorological data and detailed population information in the local domain (a square area whose center is located at the emission source and is of size 100 by 100 km) with 5 × 5 square km resolution have been included in the model, while in RUWM model, only the overall population density as a number based on person per square kilometer is sufficient (Büke and Köne 2011; Spadaro 2002b).

Meteorology and population data of receptor

For local estimation of health effects, the population data within 50 km around the emission source is required (The local domain is a square area of 100 km by 100 km, with the origin at the emission source.). The QUERI model requires population data for each 5 × 5 km^2 cells around the power plant for accurate estimation of health effects. Therefore, the population data for the urban and rural blocks were collected from Municipal Administrations and Office of the Governors. Meanwhile combining urban and rural population data of the region, local domain was gridded into 5 × 5 km^2 cells by using the ArcGIS software, Ver. 9.3, and each cell population was accurately calculated. The population density in the region beyond the radius of 50 km (regional domain) is required to estimate the regional health effects, which was calculated according to the population and area of the surrounding region.

According to the weather station deployed at the power plant, the required meteorological information were obtained, including hourly data for wind speed, wind direction, temperature, solar radiation and precipitation (for 1 year from September 2014 to November 2015). Due to lack of recorded data on cloudiness in this station, the hourly cloudiness was received from the adjacent station based on Okta unit (about 20 km at its north side). This information was integrated together due to the proximity of the two stations and similarity of regional cloudiness. The calculation related to Pasqual stability class and mixing layer height was done according to the data on wind speed, solar radiation rate and cloudiness. The depletion velocity of pollutants is associated with atmospheric and regional conditions of the area, background concentration of pollutants, etc. (Bickel and Friedrich 2005). Due to the lack of data on the depletion velocity of the pollutants in Iran and the study area, the data reported on Tunisia (Rabl et al. 2014) were used which is very similar to the study area in terms of precipitation and meteorological conditions (Azarakhshi et al. 2012; Khadivi-Khub et al. 2015; Khazaei et al. 2013). Table 1 shows the depletion velocity values used for the pollutants studied in this research. It should be noted that the depletion velocity of the CO was extracted from the factors listed in the ExternE project (Friedrich and Bickel 2001). The WRPLOT View (version 7) software was used to draw the regional wind rose. The hourly data of the wind speed and wind direction during the time of the study (September 2014 to November 2015) were used to draw the wind rose.

Table 1 Depletion velocity values of the pollutants

Pollutant	PM_{10}	NO_x	SO_2	CO	Nitrates	Sulfates
Depletion velocity (cm/s)	0.72	1.21	0.74	0.1	0.83	1.57

Estimation of pollutants dispersion

In AirPacts model, the dispersion of pollutants in locally distances was predicted by using the Gaussian model. Considering the reflective effect of the earth surface, the pollutant concentration was calculated using the following equation.

$$C_{(x,y,z)-\text{local}} = \left(\frac{Q}{2\pi u \sigma_y \sigma_z}\right) e^{\frac{-y^2}{2\sigma_y^2}} \left(e^{\frac{-(z-h_E)^2}{2\sigma_z^2}} + e^{\frac{-(z+h_E)^2}{2\sigma_z^2}}\right) \quad (1)$$

In this equation, the concentration of pollutant can be calculated in a three-dimensional form with respect to the fixed emission rate (Q) in steady state meteorological conditions.

Where, y is Crosswind distance, z is vertical height from the ground level, u is Average wind speed at the height of the stack, h_E is effective height of stack which were calculated using the Briggs equation (based on plume buoyancy flux, wind speed and atmospheric stability conditions), σ_y and σ_z are the dispersion parameters in the lateral and vertical directions of the pollutant, respectively. The values of these coefficients can be calculated according to the Pasqual stability class, type of the area and distance from the pollution source (Spadaro 2002a; Zannetti 2013).

In the regional domain, the concentrations of pollutants at a distance of r from the downwind are estimated according to the following equation:

$$C_{\text{Regional}} = \left(\frac{Q}{2\pi u h_{\text{mix}}}\right) \frac{1}{r} e^{\left(\frac{-k_{\text{uni}}}{u h_{\text{mix}}}\right) r} \quad (2)$$

Here, the h_{mix} is the mixing layer height in the atmosphere, which is also known as the planetary boundary layer and can be calculated based on atmosphere stability conditions (Pasqual stability class). The k_{uni} is also the average depletion velocity of the pollutant (Spadaro 2002a).

Estimating the health effects

The health effects (cases or years of life loss (YOLL)) for a source with continuous emission is calculated according to the IPM method as:

$$I = \int_A \rho(r) f_{\text{er}}(r, C(Q)) dA \quad (3)$$

Where, $\rho(r)$ is receptor density (persons/m^2), f_{er} is the ERF slope (cases/(person year per μg/m^3)), r is Source-receptor position vector (meter), C is incremental change in ambient air concentration at the earth's surface due to emission Q (μg/m^3) and A is Impact area (square meter) (Büke and Köne 2011; Casas-Ledon et al. 2014; Spadaro 2002a).

To calculate the health damages on a regional scale, the Eq. (4) can be extracted from the simplification of Eq. (3) based on the following assumptions:

$$I = \frac{\rho_{\text{reg}}.f_{\text{er}}.Q}{k} \cdot R \quad (4)$$

1. The pollution source (power plant) is located at the origin of the coordinate system; i.e., $r = 0$.
2. The distribution of receptor which is exposed to risk is uniform. In this case, the $\rho(r)$ has a fixed value and is shown here as ρ_{reg}.
3. The pollutant concentration $C(r, Q)$ is a ratio of the pollutant atmospheric removal flux as $M(r) = k(r)$. $C(r, Q)$, where, the $M(r)$ is the pollutant atmospheric removal flux along the ground level. Its unit is based on mass per time unit-area unit. The $k(r)$ is the depletion velocity of the pollutant, which value is assumed to be constant in the studied area. The rate of Q (μg/s) is also assumed to be steady.

In Eq. (4), R is the correction factor, which is influenced by the stack parameters (temperature, flow rate) as well as the pollutant depletion velocity. In SUWM model, with assumed constant receptor distribution, the R value will be equal to 1 (Hainoun et al. 2010; Spadaro 2002b).

The ERF is used to relate the changes in the concentration of the pollutant to a physical (health) effect on related receptors. The ERFs associated with health effects are extracted from semi- experimental linking based on epidemiological studies (Rabl 2001). From the perspective of available evidence, it is assumed that ERFs related to health, are as a straight line with no threshold and have a minimum impact at normal and current levels in the air. The effects on human health can include effects on the respiratory system (asthma attack, hospital admission, etc.) and premature deaths. The quantification of mortality known as a reduction in life expectancy is expressed as years of life lost (YOLL) in the target population under risk potential (Hainoun et al. 2010; Spadaro 2002b). The ERFs (annual cases/person.mg/m^3) are assumed to be linear with no threshold, which can be achieved based on the following equation:

$$\text{ERF} = f_{\text{er}}.C(r, Q) \quad (5)$$

As mentioned above, f_{er} is ERF slope ((cases/(person.year.mg/m^3), which can be achieved from the following equation:

$$f_{\text{er}} = \text{IRR.IR}.F_{\text{pop}} = \text{IRR.Baseline} \quad (6)$$

Here, IRR is increased risk ratio (change percentage per micrograms/m^3), IR is incidence rate (number of annual cases

Table 2 Technical specifications of power plant

Characteristic	Value
Number of stack	4
Stack diameter (m)	6
Stack height (m)	55
Exhaust velocity (m/s)	17.51
Exhaust flow rate (m^3/h)	1,793,255.19
Exhaust temperature (K^0)	396.42
Exhaust pressure (kpa)	89.79

per receptor in the considered risk for adults, children, etc.) based on the cases/year—receptor, F_{pop} is fraction of affected population (e.g., the percentage of adults in the population exposed to risk), Baseline is the nominal rate of occurrence of a specific disease (case/person—year) (Casas-Ledon et al. 2014; Hainoun et al. 2010).

Calculating the attributed health costs

To turn damages due to health effects into the cost, the number of damages and health effects calculated above should be multiplied by cost unit (U_V) (e.g., the cost for short-term mortality, long-term mortality, hospital admission due to respiratory diseases, hospital admission due to cardiovascular diseases, chronic bronchitis, the number of work days lost). The following equation shows the calculation:

$$D_i = I_i \times U_V \tag{7}$$

In this equation, D_i is cost of damages related to any of the health effects of (i) displayed as US\$/year, I_i is the health effects based on cases or YOLL and U_V is cost unit in US dollars per cases or YOLL (Casas-Ledon et al. 2014).

The costs in calculating the health effects include the costs of disease; the costs related to wages and decreased productivity. In addition to market-based costs, there are also non-market-based costs such as the costs that a person is willing to pay to prevent the risk or injury (Spadaro 2002b). The health damage costs in Europe (project ExternE) are regarded as the baseline to calculate the costs of health effects. For other countries, this cost can be multiplied by the ratio of PPPGNP

Table 3 Power plant emission factors

Pollutant	Emission rate	
	g s^{-1}	g kWh^{-1}
NO_x	262.81	1.68
SO_2	1.66	1.06×10^{-2}
CO	8.59×10^{-1}	5.49×10^{-3}
PM_{10}	5.18	3.31×10^{-2}

Table 4 Statistics of meteorological data (2014–2015)

Parameter	Unit	Value
Anemometer height	m	10
Mean ambient air temperature	K	292.5
Mean local wind speed	m/s	3.1
Mean mixing layer height	m	669.4
Pasquill stability class		
Very unstable	%	3.12
Unstable	%	25.23
Slightly unstable	%	18.82
Neutral	%	12.76
Slightly stable	%	12.12
Stable	%	27.95

(purchasing power parity GNP) to achieve the value for a new location and the Europe. Using the following equation, the cost conversion based on the country concerned (in this case, Iran) can be done:

$$U_V \text{in Iran} = U_V \text{in UE} * \left(\frac{\text{PPP GNP}_{\text{IRAN}}}{\text{PPP GNP}_{\text{EU}}}\right)\gamma \tag{8}$$

Where, γ represents the income elasticity coefficient with a standard range between 1 and 0.3. The values less than one are used for cases that the people in the studied country are willing to pay a higher percentage of their income for their health and welfare benefits compared to people who live in Europe(Casas-Ledon et al. 2014; Turtós Carbonell et al. 2007). The PPPGNP value per capita for the Islamic Republic of Iran was set at 16,140 US\$ according to the latest statistics (2014) from the World Bank of America. The index was extracted from the same source as 39,073 US\$ for Europe (Bank World Development Indicators 2014, <www.worldbank.org/data>).

Result and discussion

Power plant atmospheric emissions

The information about the source of emission (combined cycle power plant with natural gas fuel) is presented in Table 2. The average emission rates of NO_x, CO, SO_2, and PM_{10} were calculated and shown in Table 3.

As shown in Table 3, in comparison with heavy fuel power plant, the emission rates of SO_2 and CO in this power plant are lower. The low level of SO_2 is due to the minor amount of sulfur in the used natural gas fuel. The results of other studies have pointed out zero or very low values of sulfur in the exhaust of the natural gas fuel

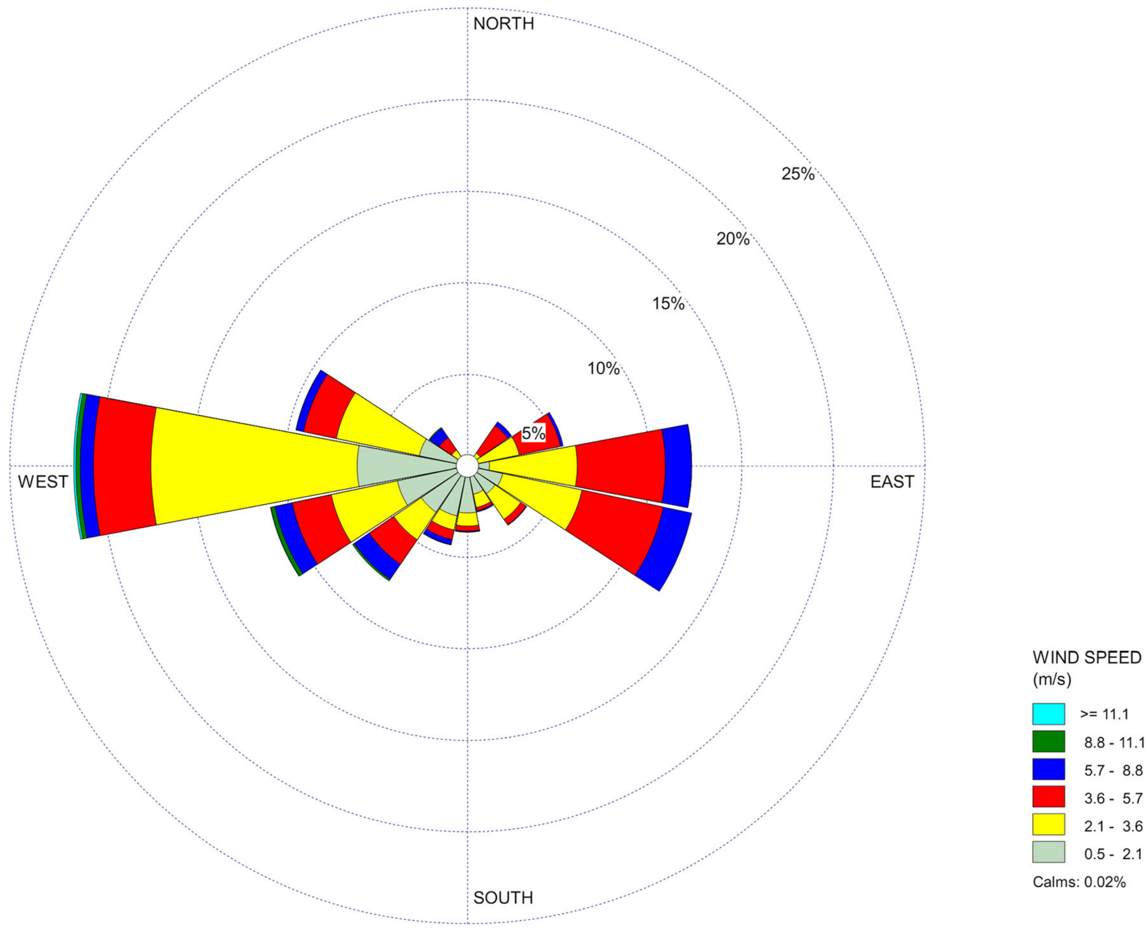

Fig. 3 Wind rose plot of power plant region considered in the study

power plant (Hainoun et al. 2010; Nazari et al. 2010; Sakulniyomporn et al. 2011). The rate of CO was low due to relatively high complete natural gas combustion process, which has been also reported in other studies conducted on gas power plants (Spath and Mann 2000).

Meteorological and population conditions of the receptor region

Table 4 shows statistics of annual meteorological data for the studied region. It is noteworthy that according to selection of QUERI model to estimate the effects and health costs, the hourly weather data are entered into the model for more precise calculation. The annual wind rose of the region is shown in Fig. 3. According to the regional wind rose and the results of Table 4, it becomes clear that the prevailing wind in the region blows from the West, the average wind speed is 3.1 m/s and the mean mixing layer height is equivalent to 669.4 m. In the studied region, the maximum and minimum stability conditions were for stable and very unstable conditions with 27.95 and 3.12 %, respectively. The stability condition of each region is different from those of other areas depending on the climate and topography. For example, in the town of Remedies in Cuba, the maximum stability condition was 57.2 % for the stable condition during 2009 (Casas-Ledon et al. 2014).

In this study, the population around the plant was estimated locally with details (5 × 5 km^2 cells at a square area size of 100 × 100 km^2). In Fig. 4 the distribution of residential blocks is shown in this area, while the population is displayed as counter plot. In this plot the (0,0) point represents the power plant location. According to this figure, the highest population density is in the range of 10 to 20 km of the East and Northeast of the plant, which is the center of the city of Qom. The population density beyond the 50 km is known as the regional population. According to the population and area of the regional domain, regional population density was calculated to be 47 persons per square kilometer. Due to the proximity of the plant to population blocks and considering that the prevailing wind in the region was toward these populated areas, the local population data was collected and processed in detail in the study.

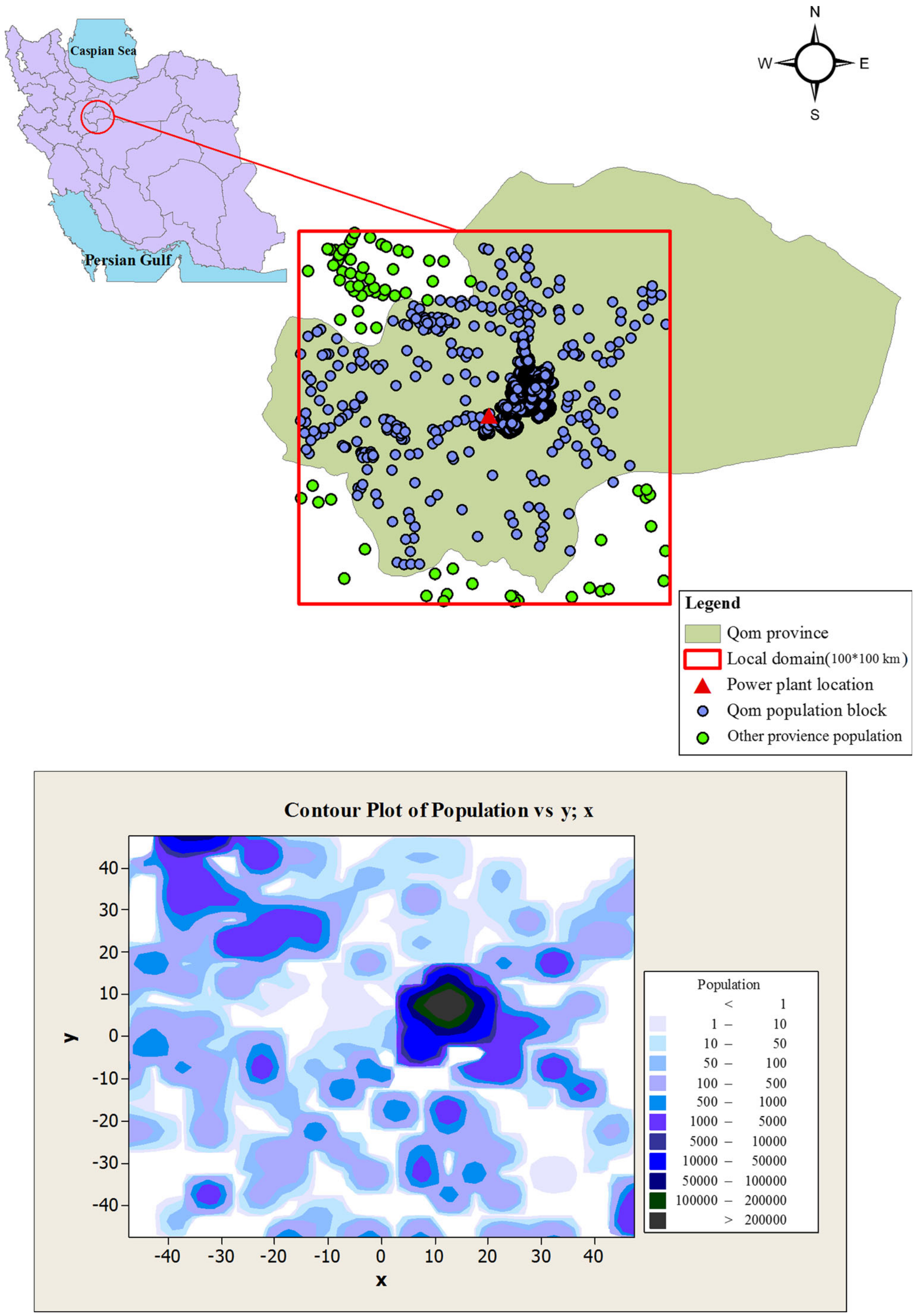

Fig. 4 Residential block and population contour plot of study area

In some similar studies, the accurate estimation of local population is also taken into account. For example, Hainoun et al. calculated these population values in a few selected areas in order to estimate the health costs of generating electricity in Syria (Hainoun et al. 2010). In examining the health effects of one of Turkey's power plants, Buke and Kone estimated the detailed information of the population for local domain (square-shaped with sides equaling 100 km^2) with the resolution of 5 × 5 km^2 (Büke and Köne 2011). However, in other studies in this field, only the population density estimation (person per square kilometer) has been considered (Casas-Ledon et al. 2014; Liun et al. 2007; Macías and Islas 2010; Turtós Carbonell et al. 2007).

Table 5 Exposure-response functions and cost unit values of health impacts

Pollutant	Health impact endpoint	F_{pop}	ERF slope	Unit cost (US$ 2000/case)
PM_{10}	Chronic bronchitis (CB)	0.68 (adults >18 years)	8.63E-06	73,444.37
	Long-term bortality (L.YOLL)	0.46 (adults >30 years)	3.61E-05	41,720.37
	Restricted activity days (RAD)	0.68 (adults >18 years; includes WDL)	1.70E-02	47.92
	Hospital admissions—cardiovascular (HA-C)	0.06 (elderly >65 years)	3.49E-06	7270.08
	Hospital admissions—respiratory (HA-R)	1 (all)	2.07E-06	1875.35
	Asthma attacks (AA)	(0.13) asthmatics	6.39E-05	82.61
	Congestive heart failure (CHF)	0.06 (elderly >65 years)	1.08E-06	1412.71
	Chronic cough (CC)	0.32 (children)	6.57E-04	104.09
Sulfate	Chronic bronchitis (CB)	0.68 (adults >18 years)	1.44E-05	73,444.37
	Long-term mortality (L.YOLL)	0.46 (adults >30 years)	6.02E-05	41,720.37
	Restricted activity days (RAD)	0.68 (adults >18 years; includes WDL)	2.83E-02	47.92
	Hospital admissions—cardiovascular (HA-C)	0.06 (elderly >65 years)	5.83E-06	7270.08
	Hospital admissions—respiratory (HA-R)	1 (all)	3.46E-06	1875.35
	Asthma attacks (AA)	(0.13) asthmatics	1.07E-04	82.61
	Congestive heart failure (CHF)	0.06(elderly >65 years)	1.80E-06	1412.71
	Chronic cough (CC)	0.32 (children)	1.11E-03	104.09
Nitrate	Chronic bronchitis (CB)	0.68 (adults >18 years)	8.63E-06	73,444.37
	Long-term mortality (L.YOLL)	0.46 (adults >30 years)	3.61E-05	41,720.37
	Restricted activity days (RAD)	0.68 (adults >18 years; includes WDL)	1.70E-02	47.92
	Hospital admissions—cardiovascular (HA-C)	0.06 (elderly >65 years)	3.49E-06	7270.08
	Hospital admissions—respiratory (HA-R)	1 (all)	2.07E-06	1875.35
	Asthma attacks (AA)	(0.13) asthmatics	6.39E-05	82.61
	Congestive heart failure (CHF)	0.06 (elderly >65 years)	1.08E-06	1412.71
	Chronic cough (CC)	0.32 (children)	6.57E-04	104.09
SO_2	Hospital admissions—respiratory (HA-R)	1 (all)	2.84E-06	1875.35
	Short-term mortality (S.YOLL)	1 (all)	2.30E-06	71,874.7
CO	Congestive heart failure (CHF)	0.06 (adults >65 years)	3.28E-08	1412.71

Human health impacts

The results of Airpacts modeling showed that the peak concentration of pollutants in the local domain occurred at $X = 7.5$ km, $Y = 2.5$ km, which is located in a town near city of Qom. The distance of the peak concentration is related to emission characteristics and meteorological conditions of the studied area (Büke and Köne 2011). The type of health effect which was considered in this study for PM_{10}, nitrate, sulfate, SO_2, and CO included: chronic bronchitis (CB), long-term mortality (L.YOLL), short-term mortality (S.YOLL), restricted activity days (RAD), cardiovascular hospital admissions (HA-C), respiratory hospital admissions (HA-R), asthma attacks (AA), congestive heart failure (CHF) and chronic cough (CC). The fraction of affected population (F_{pop}) and ERF slopes are presented in Table 5. The ERF slope (f_{er}) for each pollutant is required for the calculation of each health effect. ERF slopes were calculated by using Eq. (6), with increased risk ratio (IIR) assigned to different health impact for each pollutant (i.e., PM_{10}, sulfate, nitrate, SO_2, and CO) according to the ExternE project and Rable recommendation (Bickel and Friedrich 2005; Macías and Islas 2010; Preiss and Klotz 2007; Rabl 2001; Spadaro 2002c), incidence rate (IR) and population and health statistics from Iranian Statistics Center (ISC 2015). The considerable diversity of ERF slops in Table 5 can be assigned to the differences between IIR and F_{pop} for each health impact point and pollutant.

According to these ERF slopes, population density, meteorological condition, pollutant depletion velocities, emission factors, pollutant dispersion and concentration in local and regional domains, the total (local and regional) health effects were estimated by QUERI model, as presented in Table 6. The main health effect was assigned to nitrate as RAD with 25,240 days/year. The greatest contribution of health effects was attributed to nitrate (95.69 %). After that the contribution of health effects decreased as PM_{10} (3.78 %) > sulfate (0.53 %) > SO_2 > CO. Both the CO and SO_2 effect were

Table 6 Health impacts (cases or YOLL/year) and damage costs produced by the power plant

Pollutant	Health impact endpoint	Type of impact	Health impact (cases/year)	Damage cost (US$ 2000/year)
PM_{10}	Chronic bronchitis (CB)	Morbidity	1	3.73E + 04
	Long-term mortality (L.YOLL)	Long-term mortality	2*	8.85E + 04
	Restricted activity Days (RAD)	Morbidity	998	4.78E + 04
	Hospital admissions—cardiovascular (HA-C)	Morbidity	<1	1.49E + 03
	Hospital admissions—respiratory (HA-R)	Morbidity	<1	2.28E + 02
	Asthma attacks (AA)	Morbidity	4	3.10E + 02
	Congestive heart failure (CHF)	Morbidity	<1	8.98E + 01
	Chronic cough (CC)	Morbidity	39	4.02E + 03
Sulfate	Chronic bronchitis (CB)	Morbidity	<1	5.23E + 03
	Long-term mortality (L.YOLL)	Long-term mortality	<1*	1.24E + 04
	Restricted activity days (RAD)	Morbidity	140	6.70E + 03
	Hospital admissions—cardiovascular (HA-C)	Morbidity	<1	2.09E + 02
	Hospital admissions—respiratory (HA-R)	Morbidity	<1	3.19E + 01
	Asthma attacks (AA)	Morbidity	1	4.35E + 01
	Congestive heart failure (CHF)	Morbidity	<1	1.26E + 01
	Chronic cough (CC)	Morbidity	5	5.72E + 02
Nitrate	Chronic bronchitis (CB)	Morbidity	13	9.43E + 05
	Long-term mortality (L.YOLL)	Long-term mortality	54*	2.24E + 06
	Restricted activity days (RAD)	Morbidity	25,240	1.21E + 06
	Hospital admissions—cardiovascular (HA-C)	Morbidity	5	3.77E + 04
	Hospital admissions—respiratory (HA-R)	Morbidity	3	5.78E + 03
	Asthma attacks (AA)	Morbidity	95	7.85E + 03
	Congestive heart failure (CHF)	Morbidity	2	2.27E + 03
	Chronic cough (CC)	Morbidity	977	1.02E + 05
SO_2	Hospital admissions—respiratory (HA-R)	Morbidity	<1	9.84E + 01
	Short-term mortality (S.YOLL)	Short-term mortality	<1	3.06E + 03
CO	Congestive heart failure (CHF)	Morbidity	<1	1.88E + 00

*As YOLL/year

negligible (<0.001 %), because of the low emission rates of CO and SO_2 from combustion of natural gas. Similar to the results of the current study, in some studies conducted on natural gas power plants, the results showed that the health damage from nitrate was much higher than other those of pollutants (Hainoun et al. 2010; Macías and Islas 2010). Figure 5 illustrates the contribution of each category of health impact (case per year) for all pollutants. As demonstrated in this figure for all pollutants, the highest health impact is related to RAD (95 %), CC (4 %), and AA (0.36 %). Also, the amount and heat plot of each category of health damage for all pollutants are presented in Table 7. Macías and Islas reported that the highest health impacts produced by natural gas power plants in the Mexico City were related to RAD (99 %), emergency room visits (ERV) (0.29 %) and AA (0.24 %) (Macías and Islas 2010).

Total health damage cost

According to Eq. (8) the ratio of purchasing power parity for Iran and Europe was determined (0.413) and based on European unit damage cost from the EXTERNE project, the unit cost (US$ 2000/case) was calculated for each health impact (Table 5). By using Eq. (7) for each health impact, the total (local and regional) health damage cost was calculated as

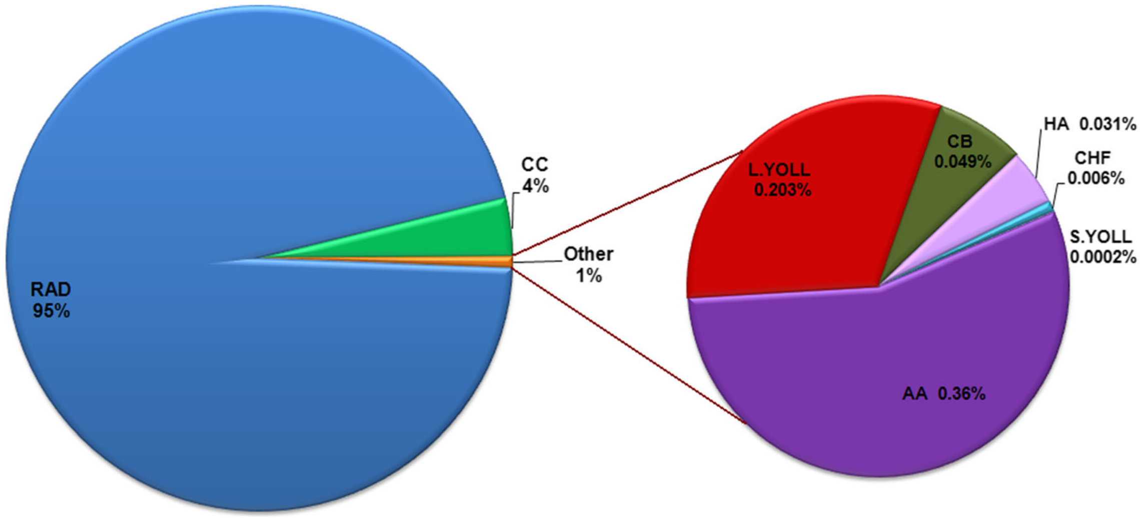

Fig. 5 Contribution of each category of health impact in the studied power plant

shown in Table 6. The highest health damage cost belonged to nitrate as L.YOLL with 2,240,000 US$/year, RAD with 1,209,000 US$/year a CB with 943,300 US$/year.

Figure 6 illustrates the contribution of costs related to each category of health damage (for all pollutants). As demonstrated in this figure for all pollutants, the maximum health damage cost is related to L.YOLL (49 %), RAD (27 %), and CB (21 %). Furthermore, the amount and heat plot of costs pertaining to each category of health damage for all pollutants are presented in Table 7. Macías and Islas reported that highest total damage costs produced by electric power plants (various types of fuels) in the Mexico City were related to L.YOLL (66 %), RAD (17 %), and CB (13 %) (Macías and Islas 2010).

Figure 7 illustrates local, regional and total health damage costs for each pollutant (sulfate, nitrate, CO, SO_2, and PM_{10}). Regarding the damage costs of pollutants varied in a wide range (around 1 for CO to 3,532,000 US$/year for nitrate), the horizontal axis of the diagram (represents as the health damage costs US$/year) is classified based on logarithmic unit. As can be seen in this figure, the damage cost of pollutant was found to decrease in the following order: nitrate > PM_{10} > sulfate > SO_2 > CO.

According to the results, regional health damage cost was more than local cost. The estimated total damage costs for this gas-fired power plant amounts to 4,755,155 US$ 2000/year and the cost per kWh of generating electricity is 0.096 US. Health damage cost for different fuel type power plant is estimated for some regions in the world. The damage cost of power plants varies according to fuel type, meteorological conditions and receptor characteristics. The fuel type has been a main factor for the damage cost difference of power plants. According to the results of other studies, among various fuels coal (Macías and Islas 2010;

Table 7 Health impacts and damage costs as heat plot for all pollutants

Type of health impact (for all pollutants)	Total health impact (cases/year)	Total damage cost (US$ 2000/year)
Chronic bronchitis (CB)	13.41888	985,818
Long-term mortality (L.YOLL)	56.0994	2,340,940
Restricted activity days (RAD)	26,377.4	1,263,499
Hospital admissions—cardiovascular (HA-C)	8.68474	45,482.66
Asthma attacks (AA)	99.3234	8204.89
Congestive heart failure (CHF)	1.680755	2375.189
Chronic cough (CC)	1021.421	106,293.6
Short-term mortality (S.YOLL)	>1	3055

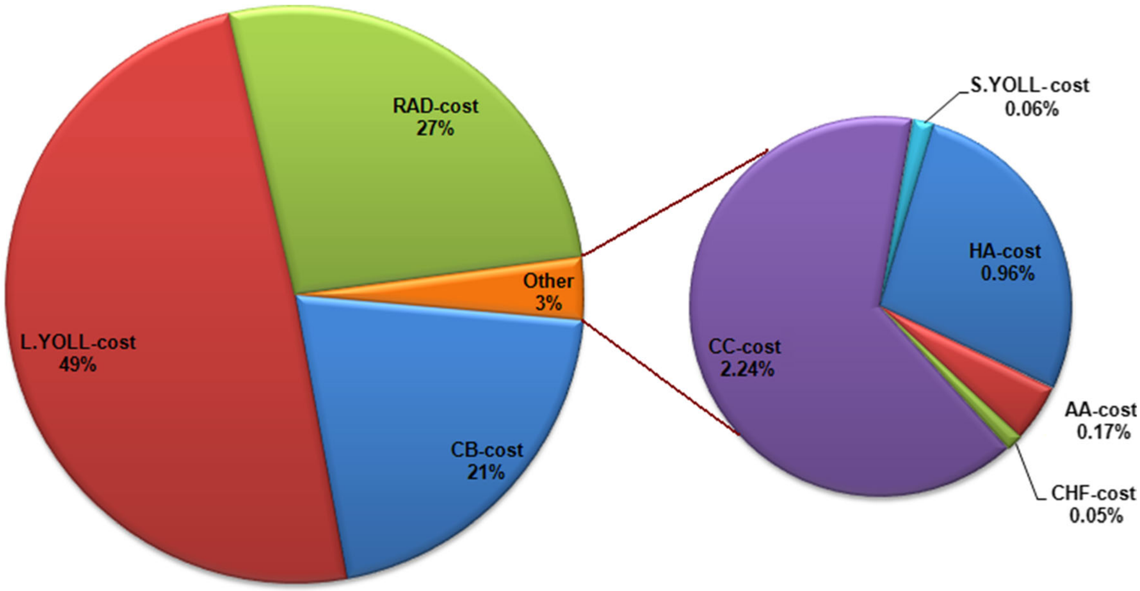

Fig. 6 Contribution of damage costs related to each category of health impact

Sakulniyomporn et al. 2011), lignite (Sakulniyomporn et al. 2011) and heavy fuel oil (Hainoun et al. 2010; Macías and Islas 2010; Turtós Carbonell et al. 2007) have had the highest costs and lowest cost were related to natural gas (Hainoun et al. 2010; Macías and Islas 2010; Sakulniyomporn et al. 2011), diesel (Sakulniyomporn et al. 2011) and ethanol (Casas-Ledon et al. 2014). Moreover, pollutant abatement technologies in power plants (e.g., flue-gas desulphurization) have had a remarkable effect on health damage cost (Büke and Köne 2011; Sakulniyomporn et al. 2011). The results of the study by Hainoun et al. showed that the total health damage cost and damage cost per generated electricity from Deir Ali natural gas-fired power plant in Syria were 3.36 million US$ and 0.06 US/kWh, respectively (Hainoun et al. 2010).

Sensitivity analysis

The most important uncertainties that may significantly influence the results of this study include the ERF slope, depletion velocity and regional receptor density. As mentioned in earlier studies for the sensitivity analysis, each of these parameters was varied separately in the range of 10 % around its nominal value, and the total health damage cost was recalculated (Büke and Köne 2011; Hainoun et al. 2010). Table 8 shows the results of the sensitivity analysis. Based on these results, an increase in the ERF slope by +10 % leads to a 10.02 % increase in total health damage costs and 10 % decrease in ERF slope leads to a 9.98 % decrease in costs. Likewise, an increase of (10 %) the regional receptor density results in

Fig. 7 Distribution of the health damage costs by types of pollutants

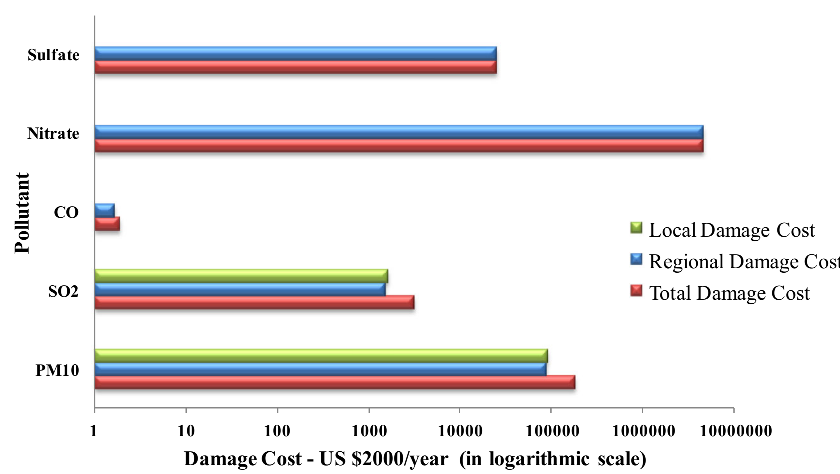

Table 8 Sensitivity of health damage cost for ERF slope (f_{er}), depletion velocity (k) and changes in regional population density (p)

Parameters	Changes	Total damage cost (thousand US$ 2000)	Relative change of total damage cost (%)
ERF slope	−10 % (f_{er})	4280.32	−9.98
	f_{er} (no change)	4755.15	0
	+10 % (f_{er})	5231.99	+10.02
Depletion velocity	−10 % (k)	5254.20	+10.49
	k (no change)	4755.15	0
	+10 % (k)	4344.57	−8.63
Regional population density	−10 % (p)	4289.58	−9.79
	p (no change)	4755.15	0
	+10 % (p)	5221.73	+9.81

an increase (9.81 %) in total damage costs. On the other hand, the depletion velocity and damage change in opposite directions, so that increasing (10 %) the depletion velocity of pollutants leads to a decrease (8.63 %) in health damage costs. As the results demonstrate, the health damage cost is sensitive to the change in these parameters.

Conclusion

The gas-fired power plants have the highest share in electricity production of Iran. To date, no study has been done to determine the associated health damage costs of these power plants. The IPA approach is a helpful and applicable method to evaluate the external health damage costs of power plants and has been widely used for environmental and health assessment and decision making for energy conversion. The results revealed that the annual health damage costs resulting from Qom gas fired power plant in 2014–2015 was approximately 4.76 million US$ 2000 and the cost per kWh of generated electricity was 0.096 US. In this estimate, the most important health damage cost is for L.YOLL, 49 % of the total, followed by RAD at 27 %, CB at 21 % and CC at 2.24 %. It was found that the major health effect was attributed to the restricted activity days (RAD) which was due to nitrate. The maximum health damage costs related to long-term mortality, RAD, and chronic bronchitis were 2,340,940, 1,263,499, and 985,818 US$ 2000/year, respectively. The emission of PM_{10}, CO, and SO_2 from burning natural gas is low and NO_x has the most share of emissions in gas fired power plant. Therefore the health damage costs from burning natural gas are solely attributable to NO_x and its derived pollutant (i.e., nitrate). In the present study, nitrates accounted for more than 95 % of the overall health damage cost. Although the health damage costs of gas-fired power plant were lower than those of other surveyed heavy fuel oil and coal-fired power plants, according to the large share of these power plants in the country and the proximity of some of them to the populated areas, it can be recommended to focus on the emission control strategies and considering the site selection for new power plants and also, to expand the constructed projects.

Acknowledgments This research was done with the financial and technical support of the Institute for Environmental Research (IER) of Tehran University of Medical Sciences (grant number: 94-01-46-28392) and tha Research Center for Environmental Pollutants, Qom University of Medical Sciences (grant number: 94589). The authors wish to express their appreciation to the Tavanir Holding Company for the technical and data support.

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