Research article

Development of a system dynamics model for dioxin flow and its application to the energy sector

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A B S T R A C T

Dioxin pollution has been problematic in Taiwan. Although the government has established emission standards and emission inventory to control dioxin pollution, such efforts only apply to pollution emissions; no attempt has been made to understand the flow of dioxins in different environmental media. In this study, the STELLA software was used to model the flow pattern of dioxins in various media. This model and the RAIDAR model established by the Canadian Environmental Model Research Center were used to simulate dioxin flow in Taiwan, and their results were compared with the measured values. The accuracies of the RAIDAR and STELLA models were 63.92% and 49.78%, respectively. This shows that the simulation with the STELLA model provided results closer to the measured values and that the error was less than ten times that of the RAIDAR model, indicating that the proposed model is predictive. In addition, we used the results of a system dynamics model for dioxin flow and an air resource co-benefits (ARCoB) model to apply the obtained results to the energy sector to quantify the co-benefits of reducing dioxin, greenhouse gas, and air pollutant emissions on the basis of the policy target for the year 2030. The total co-benefits of natural gas and renewable energy (RE) scenarios were US\$9.63 billion and US\$12.57 billion, respectively; the benefit-cost ratios were 2.89 and 20.67, respectively. The development of an RE policy as an alternative to a coal-fired power generation policy will contribute to the best co-benefits of integrated reductions and will also contribute to human health.

1. Introduction

The primary source of polychlorinated dibenzo-p-dioxin/furans, generally referred to as dioxins, is human activities, such as waste incineration, thermal power generation, energy generation, metal smelting, and chemical processes. The behavior of dioxins in the atmospheric environment includes high end bioconcentration, accumulation, and enlargement, resulting in dioxins being known as the poison of the century. More than 95% of the dioxins in humans are associated with exposure through oral intake through the food chain, and they are accumulated in the blood (WHO/ICPS, 1989). The primary entry of dioxins into the food chain is through atmospheric settlement, i.e., proliferation and settlement onto the soil, where it is absorbed by plants and ingested by animals (Olson and Morton, 2019; Kurwadkar et al., 2020).

In recent years, because of the improved control of incineration plants, thermal power plants, and steel foundries, dioxin emissions have been low even though 93.9% of the thermal power plants in Taiwan discharge emissions into the atmosphere. However, the emission factor (620 ng I-TEQ ton^{-1}) of Taiwan's coal-fired thermal power plant is much higher than the value reported for foreign power plants (2.34 ng I-TEQ ton^{-1}) (Lin 2007), thus showing that the domestic coal-fired thermal power plant air pollution control equipment in Taiwan needs to be improved to efficiently remove dioxins. The Fixed Pollution Sources of Harmful Pollutants Emissions Inventory Report of the US Environmental Protection Agency (USEPA) indicated that the iron and steel industry were the largest contributors to the total dioxin emissions. But the poor combustion techniques may release inorganic and organic pollutants into the environment through flue gas and residual ash (WHO, 1996; Porteous, 2001; Jones and Harrison, 2016; Nguyen et al., 2021).

As such, this study is focused on simulating pollutant emissions from thermal power plants and the steel industry and on reducing dioxins in different contexts.

Dioxins are highly stable and difficult to decompose, which leads to their environmental acuity (Hogarth et al., 2018; Kurwadkar et al., 2020). Upon their entry into the food chain, where they undergo bioaccumulation and biomagnification effects, they can be concentrated more than ten thousand times. The World Health Organization (WHO) has pointed out that ~95% of the body's absorption of dioxins originates

from food exposure and that dioxins are hydrophobic and fat soluble; therefore, they are easily stored in human and animal adipose tissue and cannot be easily metabolized or excreted (WHO/ICPS, 1989). Pirkle et al. (1989) reported that the half-life dioxins in the body is approximately 7–11 years and that long-term accumulation will cause great harm to human health.

Dioxins include a wide array of compounds. The International Agency for Research on Cancer (IARC) ranked the most toxic 2,3,7,8-TCDD dioxin/furan as carcinogenic to humans in 1997 (IARC, 1997a,b). The National Institute for Occupational Safety and Health (NIOSH) in the United States classifies dioxins/furans as possible occupational carcinogens (NIOSH, 1986). Dioxins have been demonstrated to be present in various media, including air, soil, water, sediment, and organisms. Because numerous sources of pollution (e.g., high-temperature processes, incineration of waste, and industrial processes) can discharge dioxins and because these compounds are resistant to biological transformation and non-biological decomposition, the discharged transmission distance to the atmosphere for dioxins is quite long (i.e., until dioxins deposit via the dry and wet settlement functions onto the surfaces of plant, soil, and water (Hites and Harless 1989; Olson and Morton, 2019; Kurwadkar et al., 2020).

Exposure to dioxins occurs through the following three main paths: inhalation, skin contact, and ingestion. The WHO/ICPS, 1989 estimated that more than 95% of blood dioxin exposure is from the consumption of food, particularly fish, meat, and dairy products, containing dioxins. The USEPA (1994) noted that, given the typical diet of people in North America, 93% of the population is exposed to blood dioxins from meat and dairy products, 23% is exposed to dioxins in dairy products and milk; other larger sources of exposure include beef, fish, pork, poultry, and eggs. Because dioxins are fat soluble, fish easily bioaccumulate them through the food chain, usually in concentrations much higher than the dioxin concentration in water in the environment. High dioxin concentrations even occur in women's breast milk, thus exposing newborns to dioxin through breastfeeding (Schuhmacher et al., 2019).

In the past, incinerators were catalogued as important sources of polychlorinated dibenzo-p-dioxin/furans (Hutzinger and Fiedler, 1989; Schuhmacher et al., 2019). Chen (2004) used multiple regression analysis to perform blood dioxin analysis for residents living in the vicinity of an incinerator, adjusting for age, sex, smoking habits, and body fat. The results showed that the intake of seawater fish and the concentration of dioxins in the blood showed a significant positive correlation. Exposure of the human body to dioxins in the air was found to represent only 2.6% of the blood dioxin. In addition, public living patterns affect people's feeding habits; people who live in coastal areas or near a fishery may consume more seafood than those living in other areas, thus resulting in a high concentration of dioxins in the blood.

New Zealand's Environmental Protection Authority performed a cost-benefit analysis of emission reduction measures for each sector (i.e., incinerators, nonferrous metal foundries, wood-fired boilers, and coal-fired boilers) in 2001; the corresponding report was based primarily on section 32 of the Resource Management Act of 1991, which requires that alternatives and benefits and cost analyses should be considered in the development of policies or programs. The method used in the report is the result of each dioxin control method of cost-effectiveness analysis, which is presented in terms of the cost of reduction divided by the dioxin emission reduction. The lower the ratio, the more efficient the control method. The combustion of coal-fired boilers ca These plants are eaten by animals, leading to n be reduced through the following two approaches: (1) installing pollution control equipment and (2) using natural gas instead of coal-fired power generation. In the device pollution control equipment, the installation of catalyst fiber filters is the most efficient method of dioxin emission reduction; with respect to alternative energy sources, the use of natural gas is more efficient than the use of fuel.

In the present study, we used the air resource co-benefits (ARCoB) model, which was developed using a simple box model, local statistical data, and air pollution control regulations in Taiwan (Chen et al., 2017).

The ARCoB model has been found to increase economic viability of emission controls and to help local and central governments improve air quality and ensure that greenhouse gases (GHGs) are efficiently reduced (Chen et al., 2013). In addition, criteria air pollutants (CAPs), GHGs, and dioxins have been incorporated into this model to assess the circumstances of air pollutant (AP) reduction in each situation and to integrate the results of the reduction of benefit analysis to enhance air quality management policy assessments. Furthermore, the ARCoB model has been used in the energy sector as a method to demonstrate the integrated analysis results.

Hence, in the present study, we set up a dioxin flow model using the STELLA software to assess the different environmental media after dioxin pollution emission. Then, we apply the results to the energy sector for emission reduction and quantify the co-benefits of reducing the emissions of dioxins, GHGs, and APs on the basis of the policy target for the year 2030.

2. Methods

2.1. Dioxin flow setup

This study was conducted through the system dynamic computer simulation software suite STELLA (isee systems, USA). The STELLA model is closely related to the evolution of time, thus making it suitable for investigating the effects of time on the subject under investigation. The STELLA software contains several components, including stock, flow, auxiliary, and information. The flow is a block that accumulates over time in the same manner as a bucket according to the size of a faucet opening to determine the amount of water flowing into the bucket; thus, the stock, indicating that the state has been changed, represents the amount of accumulation in the system. This study is divided into four reservoirs representing the atmosphere, soil, fresh water, and ocean.

In this study, we used the STELLA version 9.0 software to model dioxin exposure in the environment and in the human body. The advantages of this software in addition to providing a clear understanding of the interrelationship between the media include the ability to model a non-linear, hysteretic system. The media can flow and provide feedback for each other, where M_i represents i storage quality. The environmental media are divided into air, soil, fresh water, and marine reservoirs, numbered 1, 2, 3, and 4, respectively, and $F_{i,j}$ represents the transmission from i to j. The system dynamic model of the dioxin flow is shown in Figure 1.

2.2. Scenario definition in the energy sector

According to the *Sustainable Energy Policy Program - Energy Conservation and Carbon Reduction Program* approved by the Executive Yuan (2008), China's clean energy target is to increase the use of low-carbon natural gas. In 2025, gas power generation is projected to account for 25% of the total generating capacity. With the active development of carbon-free RE, the effective use of RE is projected to result in an RE capacity of 8% of the total generating capacity by 2025.

According to the New Energy Policy (Ministry of Economic Affairs, 2011), *to ensure that the nuclear safety, robust reduction, to create a green low-carbon environment, and gradually toward non-nuclear homes* as the overall energy development vision and promote spindle, in the robust reduction targets proposed that the nuclear power plant is not detained, the nuclear four must ensure the safety before the business, stabilized the business of nuclear four two units before 2016, the nuclear 1 will be with the early stop. In 2025, the production capacity in Taiwan is expected to be reduced by ~514 MW because of decommissioned devices, which will result in a shortage of energy. Therefore, the Taiwan Electric Power Company has developed an alternative plan. Their study assumes that the decrease in capacity due to the decommissioning of nuclear plants 1, 2, and 3 will be ~5.14 MW, while nuclear plant 4 will be stable in 2016. The capacity of nuclear plant 4 is 2.7 MW, which still results in a capacity loss
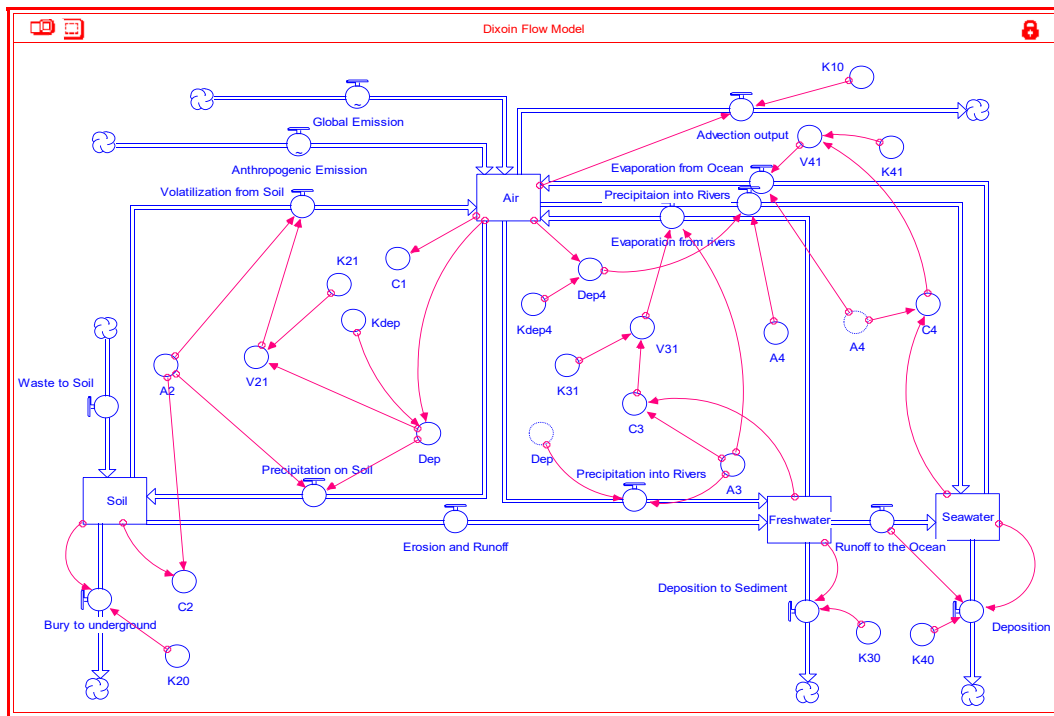
Figure 1. System dynamic model of dioxin flow used in STELLA version 9.0.

of 2.44 MW. Their study assumes that lost power generation capacity will be replaced by gas generation capacity.

According to *the long-term load forecast and power development plan summary report in 2011 to 2020* (Ministry of Economic Affairs Energy Bureau, 2012), the national power supply will increase from 240 billion kWh in 2009 to 374.7 billion kWh in 2025. With an average annual growth rate of 2.4%, coal-fired power generation in the year of 2020 will reach 24.34 million, accounting for 38.3% of the total capacity of Taiwan. According to the New Energy Policy (Ministry of Economic Affairs, 2011), the total installed capacity of renewable energy (RE) in 2030 will reach 12.5 million (16.1% of the total capacity of the total generating capacity). Through the *thousand wind turbines of land and sea*, and *million sunroofs* RE plan, the capacity of wind power and solar photovoltaic devices will reach 42 million and 31 million, respectively, by 2030. On the basis of the aforementioned objectives, the situation is divided into three scenarios, as outlined in Table 1.

2.3. Using the model and tools

This study establishes a linear relationship between various AP concentrations and emissions with the Rollback model to simplify the process of reducing medical costs and mortality from assessments of AP

reductions, thus reducing the extent of pollution reduction and the health benefits to a general linear relationship. In addition, we used the ARCoB model (Chen et al., 2017) to quantify the comprehensive environmental benefits of reductions of environmental pollutants (PM_{10}, SO_2, NO_x, and O_3) and GHGs (mainly CO_2) after implementing the policy. Recently, the issues of co-benefits of local CAPs reduction and GHG reduction have been widely discussed (Bailey et al., 2008; Chae 2010; Chae and Park 2011; Li and Crawford-Brown 2011; Anenberg et al., 2012; Crawford-Brown et al., 2012; Mao et al., 2012; Shakya et al., 2012; Takeshita 2012; Zhang et al., 2012; Chen et al., 2013). The ARCoB model was developed using a simple box model, local statistical data, and air pollution control regulations in Taiwan. The proposed ARCoB model quantified the health benefits of PM_{10}, SO_2, NO_x, CO_2, and O_3 reductions simultaneously. This model can increase the economic viability of emission controls and enable local and central governments to improve air quality and abate GHG emissions properly and efficiently (Chen et al., 2013). In addition, the ARCoB model provides guidance for the completion of work or the establishment of systems and refers to the representation of a real-world phenomenon. Numerous other researchers have also recently applied the ARCoB model (Shih et al., 2016; Chen et al., 2017; Tseng et al., 2017).

Russell et al. (1995) defined the maximum increment reactivity as the maximum sensitivity to the peak temperature of the VOCs in the initial

Table 1. Scenarios definition in the energy sector.

Scenario assumption	Coal-fired power generation	Gas power generation	Renewable energy	Nuclear power generation
BAU	Future increase in electricity demand is supplied by coal-fired power plants	Nuclear power plants 1–3 will not be extended, nuclear plant 4 remains in operation, and gas will make up for the power shortage	Maintain electricity generation in 2011	Nuclear power plants 1–3 will not be extended and nuclear plant 4 is in operation
NG	Part of the electricity demand is met by gas power generation	In 2025 will account for more than 25% of generated power	Maintain electricity generation in 2011	Nuclear power plants 1–3 will not be extended and nuclear plant 4 is stable in operation
RE	Part of the electricity demand is met by renewable energy power generation	Nuclear power plants 1–3 will not be extended, nuclear plant 4 remains in operation, and gas will make up for the power shortage	By 2030, 12,500 MW will be generated by RE	Nuclear power plants 1–3 will not be extended and nuclear plant 4 is stable in operation

Table 2. Proportion of each NMHC species and MOIR value in thermal power plants.

Type	VOC Species	Proportion (%)	MOIR (g O₃/g VOCs)
Thermal power plant	*N*-BUTANE	0.98	0.76
	1-Butene	0.79	3.82
	CIS-2-Pentene	1.05	3.94
	1-Decene	2.67	0.98
	2,4-Dimethylpentane	6.39	0.90
	Ethane	2.09	0.01
	Ethylbenzene	11.25	2.17
	N-Heptane	1.50	0.73
	Heptene	3.69	1.91
	N-Hexane	9.45	0.84
	1-Hexane	3.63	Non-MOIR
	Isopentane	1.22	0.93
	Propane	1.78	0.34
	Toluene	5.62	1.36
	M-Xylene	39.23	3.09
	O-Xylene	8.66	2.51

environment or under the discharge conditions; it is mathematically defined as follows:

$$MOIR = \max\left(\frac{\partial[O_3]_p}{\partial E_i}\right) \text{for all VOCs/NO}_x \ \ldots \qquad (1)$$

In this study, the MOIR values used in the energy scenario refer to the proportion of NMHC species in thermal power plants in the USEPA Emission Coefficient AP-42 SPECIATE database (Xu 2010). The ratio of VOCs species in each region was weighted according to its percentage by multiplying it by the MOIR value for each NMHC species; the average MOIR value was 2.09. The proportion of the NMHC species in the thermal power plant and the MOIR values are shown in Table 2.

3. Results and discussion

In this study, the dioxin flow and co-benefits with an emphasis on the energy sector in the policy target year 2030 are established and quantified using the STELLA and ARCoB models, respectively. The model in the dioxin flow used by STELLA is compared with and verified against the RAIDAR model established by the Canadian Environmental Model Research Center to simulate the results of dioxin flow in Taiwan, and the

Table 4. Trend of environment media dioxin concentration in the energy sector scenario.

Scenario	Air (pg/Nm³)	Soil (pg/g)	Fresh Water (pg/L)	Sea Water (pg/L)
BAU	0.357306	3.974950	0.044686	0.019434
NG	0.356291	3.974240	0.044559	0.019408
RE	0.356096	3.974100	0.044535	0.019403
NG compared to BAU reduction %	0.28%	0.02%	0.28%	0.13%
RE Compared to BAU reduction %	0.34%	0.02%	0.34%	0.16%

measured values are compared with the simulated values. The results show that the percentage accuracies of the RAIDAR and STELLA models are 63.92% and 49.78%, respectively. Thus, the STELLA model is closer to the measured value and that the error is less than ten times that of the RAIDAR model, thus indicating that the model constructed in this study is predictive. Hope (2008) pointed out that the purpose of model calibration is to find the same trend in the concentration of atmospheric dioxins and the total release to the atmosphere and to compare the correlation between the measured value and the simulated value to confirm that the model has considerable predictive power.

In this study, we reviewed the literature on the concentration of dioxins in each medium and compared the simulated values obtained using the STELLA and RAIDAR models with the measured values. The results are shown in Table 3. The average error values of the RAIDAR Level II, RAIDAR Level III, and STELLA models are approximately 63.92%, 85.26%, and 49.78%, respectively. Compared with the RAIDAR mode, the STELLA model can predict the concentration of dioxin in each medium accurately. Except for the egg and chicken media models, other analog predictions and domestic measured values are less than 10 times the error. Hope (2008) simulated the error of PCB flow and compared the results with measured values and achieved the same results as those found in the present study, thus demonstrating that the estimation provided by the model is reasonable. One possible cause of the error is that, in the course of the calculation, the result is produced by reference to foreign literature because of a lack of partial parameters for the country of interest.

Dioxins discharged from a source of pollution to the environment will spread and transmit in different media or flow from the system as time passes. Human dioxin exposure will vary depending on the difference in dioxin concentration in each medium. We applied the results established by the STELLA model to the energy sector. The trends of environment

Table 3. Comparison of the estimated values of the dioxin concentration model and the measured values.

Media	Unit	Time	RAIDAR Level II	RAIDAR Level III	STELLA	OBSERVED*	Error (%)
Air	pg I-TEQ/Nm³	2008	1.340×10^{-5}	2.020×10^{-4}	0.359	0.210	70.95%
Soil	pg I-TEQ/g	2005	0.521	3.910×10^{-4}	3.953	3.890	1.61%
Fresh Water	pg I-TEQ/L	2008	0.455	4.840	0.045	0.044	4.12%
Sea Water	pg I-TEQ/L	2008	-	-	0.020	0.019	4.91%
Vegetation	pg I-TEQ/g	2003	0.717	1.080	1.813	1.332	36.12%
Beef	pg I-TEQ/g	2004	1.120	16.800	0.973	0.967 ± 0.692	0.66%
Milk	pg I-TEQ/g	2004	0.155	2.330	0.256	1.34 ± 0.84	80.93%
		2010	0.155	2.330	0.256	0.564	54.59%
Pork	pg I-TEQ/g	2004	1.010	15.000	0.128	0.306 ± 0.214	58.04%
Chicken	pg I-TEQ/g	2004	0.310	4.660	0.009	0.727 ± 0.429	98.82%
Egg	pg I-TEQ/g	2004	0.269	4.060	0.005	0.909 ± 0.12	99.50%
		2010	0.269	4.060	0.005	0.400	98.86%
Fresh Fish	pg I-TEQ/g	2004	-	-	0.319	1.850 ± 0.36	82.76%
Sea Fish	pg I-TEQ/g	2004	1.510	0.371	1.297	4.700 ± 3.82	72.40%
Average error	%		63.92%	85.26%	49.78%	-	-

Note:'OBSERVED *' is corrected by references paper.

Table 5. Trend of biomass media dioxin concentrations under various energy sector scenarios.

Scenario	Pork (pg/g)	Beef (pg/g)	Milk (pg/g)	Fresh Fish (pg/g)	Sea Fish (pg/g)	Vegetable (pg/g)
BAU	0.128979	0.981639	0.257259	0.259176	1.139950	1.828480
NG	0.128956	0.981464	0.257213	0.258444	1.138430	1.828150
RE	0.128952	0.981430	0.257204	0.258303	1.138140	1.828090
NG compared to BAU reduction %	0.02%	0.02%	0.02%	0.28%	0.13%	0.02%
RE compared to BAU reduction %	0.02%	0.02%	0.02%	0.34%	0.16%	0.02%

media dioxin concentrations were compared in air, soil, fresh water, and sea water; the dioxin concentrations of air, fresh water, and sea water media in the NG scenario and the RE scenario were similar to those in the BAU scenario. In addition, the reduction percentage of the RE scenario was higher than that of the NG scenario, particularly in air and fresh water, where the reduction percentage in the RE scenario was 0.34%. The trends of dioxin concentration in each medium in the energy sector scenarios are shown in Table 4.

The media dioxin concentrations in pork, beef, milk, vegetable, and other food media were simulated under each energy scenario. Because of the food chain mechanism of dioxins, vegetables will first absorb dioxins through the soil. The consumption of the plants by animals will lead to the presence of dioxin in vegetables, milk, beef, pork, and other food media. We also applied the results established by the STELLA model to the energy sector. The trend of biomass media dioxin concentration was evaluated for pork, beef, milk, fresh fish, sea fish, and vegetables; the

dioxin concentrations in fresh fish and sea fish in the NG scenario and RE scenario were similar to those in the BAU scenario, while the dioxin concentrations in pork, beef, milk, and vegetable were not similar. The reduction percentage under the RE scenario was higher than that under the NG scenario, particularly in the fresh fish, where the reduction percentage under the RE scenario was 0.34%. The trend of each biomass medium dioxin concentration with the energy sector scenarios is shown in Table 5 (see Table 6).

In addition, we applied the results of the system dynamics model for dioxin flow and the ARCoB model to the energy sector to quantify the co-benefits of reducing dioxin, GHG, and AP emissions on the basis of the policy target for 2030.

We adopted the structure and method recently reported for the ARCoB model (Chen et al., 2013a,b) to calculate the external benefits, i.e., the reduction in external costs. The items included the averted medical expenditures with reduction of APs, the averted life expectancy value loss with reduction of APs, the averted medical expenditure with reduction of dioxins (non-carcinogen), the averted life expectancy value loss with reduction of dioxins (non-carcinogen), the averted medical expenditure with reduction of dioxins (carcinogen), the averted life expectancy value loss with reduction of dioxins (carcinogen), the saved medical expenditures with climate change, the saved agricultural economic loss, the saved life expectancy value loss, and the saved environmental cost with reduction of APs. The total benefit was included in the aforementioned results, and the total cost included the established cost and the operating cost. The total benefit in the NG scenario and the RE scenario was US$9.63 billion and US$12.57 billion, respectively; thus, the RE scenario saved more costs than the NG scenario on the basis of the 2030 policy target. In addition, the benefit-cost ratio of the NG scenario and the RE scenario was 2.89 and 20.67, respectively. The development of an RE policy provides an alternative to coal-fired power generation policy with the best co-benefits of integrated reductions, and it will also contribute to the improvement of human health.

4. Conclusions

In this study, we used the STELLA system dynamics model and the RAIDAR model established by the Canadian Environmental Model Research Center to simulate the scenarios of dioxin flow and compared the measured values and the model-estimated values for the same year. The results show that the average of the RAIDAR Level II, RAIDAR Level III, and STELLA error values are approximately 63.92%, 85.26%, and 49.78%, respectively, demonstrating that the STELLA model can accurately predict the dioxin concentration in each medium compared with the RAIDAR models. The results show that, in addition to eggs and chicken media, the other simulation and domestic measured values of the error are ten times less, thus indicating that the model proposed in this study gives feasible predictions. The possible cause of the error is that, in the course of the calculation, the result is produced by reference to foreign literature because of a lack of partial parameters in the country of study.

When the results of STELLA were applied to the trend of environmental media and biomass media on dioxin concentration in the energy sector, we found that, compared with the BAU scenario, the reduction percentage of the RE scenario is higher than that of the NG scenario. In addition, we evaluated the advantages of established policies for RE and

Table 6. Benefit-cost ratio for each scenario in the energy sector.

Item (unit: billion)		Code	NG	RE
External benefits (reducing external cost)	Averted medical expenditure with reduction of APs	A	0.06	0.13
	Averted life expectancy value loss with reduction of APs	B	7.39	7.67
	Averted medical expenditure with dioxin reductions (non-carcinogen)	C	0.0001	0.0001
	Averted life expectancy value loss with dioxin reductions (non-carcinogen)	D	0.0021	0.0017
	Averted medical expenditure with dioxin reductions (carcinogen)	E	0.000004	0.000003
	Averted life expectancy value loss with dioxin reductions (carcinogen)	F	0.0018	0.0015
	Saved medical expenditure with climate change	G	2.13	4.67
	Saved agricultural economic loss	H	0.03	0.07
	Saved life expectancy value loss	I	0.01	0.03
	Saved environmental cost with APs reductions	J	0.01	0.01
Total benefit		E = A + B + C + D L = E + F + G + H + I + J	9.63	12.57
Total cost		M	3.34	0.61
Benefit-cost ratio		N = L/M	2.89	20.67

Note: APs = air pollutants; the total cost includes the established cost and operating cost; established cost refers to the policy implemented at the first payment; operating cost refers to the policy implemented at the final payment.

combustion of NG to replace coal-fired power generation. The 2030 policy target year assumes full development of coal-fired power generation (BAU scenario), development of RE alternative coal-fired power generation (RE scenario), and the development of gas power generation instead of coal-fired power generation (NG scenario). We analyzed the benefit-cost ratios of these scenarios using the STELLA results. The co-benefits of dioxin, GHG emission (mainly CO_2), and AP reductions were based on the policy target for 2030. The total co-benefits of NG scenarios and RE scenarios were US$9.63 billion and US$12.57 billion, respectively, and the benefit-cost ratios were 2.89 and 20.67, respectively. Hence, development of an RE policy, which offers the best co-benefits of integrated reductions among the investigated scenarios, will provide an alternative to the coal-fired power generation policy and will also contribute to the improvement of human health.

Our results suggest that the atmosphere can be included in the atmosphere diffusion model in the future to simulate the concentration of dioxins in the atmosphere after the discharge of the fixed pollution sources. On the basis of this study, the STELLA dioxin flow pattern was established. The combination of the counties and cities administrative area and block simulated by the model with calculations in each county and city will enable increasingly accurate simulations of the pollutant concentrations in the air, soil, drinking water, and various types of food, thus enabling an assessment of the risk of each fixed pollution source of dioxin emissions to the health of the surrounding residents.

Although the dioxin emissions inventory has been established in Taiwan, its emissions are estimated on the basis of the average emission factor, while the actual emission factor will vary depending on the circumstances (e.g., feed size, operating conditions). Thus, the use of an average emission factor to calculate the yearly emissions cannot actually reflect the real situation in a given year; thus, the establishment of an emission factor that corresponds to different circumstances is recommended.

The EPD has brought incinerators, steelmaking electric arc furnaces, steel sintering plants, and steel dust and other fixed materials under control. The dioxin reduction effectiveness has shown a substantial downward trend each year. The results of the present study showed that the proportion of emissions from the energy sector trended upward year-by-year in the past. We recommend that strict dioxin emission standards should be set for coal-fired power plants and for the iron and steel industry in the future.

Declarations

Author contribution statement

Chao-Heng Tseng: Conceived and designed the experiments; Performed the experiments.

Ling-Ling Chen: Contributed reagents, materials, analysis tools or data; Wrote the paper.

Shang-Ming Su: Analyzed and interpreted the data.

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Data availability statement

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Declaration of interests statement

The authors declare no conflict of interest.

Additional information

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