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Distributional effects of carbon taxation

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HIGHLIGHTS

- Distributional effects of carbon tax within both household and economic sectors are examined.
- The effects of ex-ante and ex-post preferential measures are categorized and compared.
- We analyze the progress and shortcomings of existing studies.
- We put forward implications for policy-making and future research.

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ABSTRACT

The carbon tax is a frequently discussed economic instrument for carbon emissions mitigation and prevention of global climate change. However, a range of issues may emerge when introducing a carbon tax; among these issues, the distributional impact has been frequently highlighted as an obstacle to the public acceptance of such a mitigation policy. This literature review focuses specifically on the distributional effects of carbon taxes and contributes to existing studies by providing a classification and discussion on how to comprehensively assess distributional impacts and what measures can be taken to mitigate the potential adverse distributional impact. We confirm that a pure carbon tax without revenue recycling in developed economies tends to be regressive, i.e. lower income households being more affected, while our research does not support the perception that it reveals progressivity in developing countries. In terms of its effects on economic sectors, we find that sectors with higher energy intensity are more affected by a uniform carbon tax, while preferential measures to protect these industries face a trade-off between environmental effectiveness and economic growth. We also stress that different designs for carbon tax mechanisms play a key role in affecting the distributional impacts and impacts in other policy arenas, indicating that trade-offs between efficiency and equity always exist when designing a carbon tax. This study may help to identify the shortcomings of existing designs and puts forward practical implications for future research; moreover, it offers valuable information to help policy-makers to understand the trade-off between equity and efficiency when designing a carbon tax.

1. Introduction

A carbon tax is a tax levied on one or several greenhouse gas (GHG) emissions associated with the combustion of fossil fuels. In practice, such a tax is often introduced based on the carbon content of fossil fuels. A carbon tax is a type of Pigouvian taxes which are levied on market activities that generate negative externalities. In 1920, the British economist Arthur C. Pigou argued in his seminal book "The Economics of Welfare" that when the marginal social cost of a market activity diverges from the marginal private cost, the market is not efficient and will lead to an oversupply of such a product; at the same time the producer has no incentive to internalize the marginal social cost, which will lead to economic externalities [1]. GHG emissions are an example of such an externality. The basic idea of any GHG taxation is based on this Pigouvian tax that aims to internalize the cost of the externalities into the market price in order to achieve a reduction in GHG emissions and hence to mitigate climate change.

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One of the earliest propositions of a carbon tax was proposed by Ridley Nicholas, the former environment minister of the UK, and then was echoed in the Department of Environment's Pearce report [2] as a method of putting a price on environmental benefits and losses [3]. However, this particular report and many other such reports have meanwhile been added to the public discourse, and the academic literature is unanimous in the assessment of these types of taxes as a cost-effective instrument to internalize externalities [4], and yet, most countries have not implemented such as tax. Criticism came, on one hand, from questioning the science of climate change and its potential human contribution as well as its harm to society [5,6], and on the other hand were based on doubting the effectiveness of a carbon tax [3,5,7,8]. However, with the impetus of ongoing international climate negotiations and the increasing urgency of action following the Paris negotiation, the carbon tax as an economic instrument for climate change mitigation has received increasing attention.[1]

Meanwhile, the effectiveness of a carbon tax on carbon emissions mitigation has been frequently shown [10–13]. Indeed, since the carbon tax was first implemented in Finland, Poland, Sweden, Norway and Denmark in the 1990s, additional countries/region s—including Latvia (in 1995), Slovenia (in 1996), Estonia (in 2000), Switzerland (in 2008), British Columbia (in 2008), Ireland (in 2010), Iceland (in 2010), Japan (in 2012), France (in 2014), Mexico (in 2014) and Portugal (in 2015)—introduced a carbon tax; and the governments of South Africa and Chile have issued policy documents to tax carbon from 2016 and 2018, respectively; moreover, China and South Korea are also considering the introduction of a carbon tax [14]. Ex-post evaluations of carbon tax schemes have shown that a carbon tax could contribute to a reduction in CO_2 emissions. For example, Andersen [15] surveyed 20 ex-post studies for the Nordic countries, concluding that carbon emissions were curbed when compared to business-as-usual forecasts. Of these countries, Norway's carbon tax had reduced the household emissions by 3–4% between 1991 and 1993; and in Denmark, a 7% decline in industrial CO_2 emissions had been achieved from 1991 to 1997 while total industrial output increased by 27% [15]. Similarly, an IPCC report [10] shows that emissions in Sweden were 9% lower in 2007 compared to 1990. In addition, ex-ante simulations also support the tax's effectiveness [16,17]. For example, Meng et al. [18] found that a carbon tax of \$23/tCO_2 in Australia could cut emissions with a 12% reduction rate in 2004–2005; Cabalu et al. [19] showed that a \$5/tCO_2 carbon tax may potentially reduce Philippine's emissions by 9.8% to 2020. Based on a literature review, the IPCC [10] reported that 10% higher fuel prices might lead to roughly a 7% reduction in fuel use and emissions in the long run.

However, many countries that are experiencing the pressure to control CO_2 emissions are still hesitant to take actions to implement a carbon/GHG tax or a carbon emission trading scheme, despite the scientific evidence on their effectiveness in reducing energy consumption and associated emissions. An important reason for this situation is that environmental taxes often face political opposition from both the industry and the public [20]. There are many cases of failed tax initiatives, such as the energy tax in the US in 1993, the fuel tax escalator in the UK in 2000, a fossil fuels tax in Switzerland in 2000, a road pricing in Edinburgh in 2005, and the French carbon tax in 2010 to name just a few [20]. Some of the arguments fielded by the opposition are that carbon taxes tend to negatively affect GDP growth [19,21–23] and international competitiveness of industries [24,25], as well as leading to regressive distributional effects [4,11,12,26]. The potential adverse distributional impact is frequently seen as one of the main obstacles [4,27,28]. Due to differences in income, living conditions, consumption preferences and patterns, different socio-economic groups would react differently to the same stimuli [13,29,30]. The concern that the tax burden will fall more heavily on the poor is seen as a major obstacle to its policy acceptability because poor people often spend a larger proportion of income on energy-intensive products to meet their basic needs (e.g. house heating, electricity) and lack options for substitution [27,31,32]. In addition, special interest groups, energy intensive sectors and especially the fossil fuel industry have been very effective to lobby against the introduction of such taxes [20,33], making the distributional impact across industries worthy of emphasis.

So far, numerous studies have been conducted on the effectiveness of carbon taxes, and numerous studies have also focused on the distributional aspects but a comprehensive review of these studies is currently lacking. Therefore, the aim of this study is to provide such a review looking specifically at the distributional effect of carbon taxation across household groups and economic sectors.

2. Overview of carbon taxation designs

There are winners and losers when a carbon tax is introduced in an economy. Fig. 1 shows how the effects of a carbon tax are conveyed to each category of economic agents through the processes of primary distribution and redistribution of national income[2] in the short run. As shown in Fig. 1, on one hand, taxing carbon will directly lead to higher energy prices and thus increase the energy cost of a production sector; then the sector might respond to such a cost increase by adjusting its inputs and outputs. The adjustment of sectoral inputs includes inputs from other sectors as well as labor and capital inputs. Changes to its outputs will affect revenues and associated taxes [36]. Carbon tax revenues will provide an income stream to the government and increase the government share of GDP or be cycled back to tax payers. For enterprises, the price elasticities of their products will determine to a large extent if they can easily transfer their tax burden to consumers or not. Sectors producing higher price elasticity products may have to absorb the tax burden; meanwhile they might encounter a sales decrease thus eventually resulting in a profit loss. For consumers, they not only bear the direct and indirect tax burden due to the price increase of energy and other goods and services, but are also affected from the changes in their labor and capital income caused by the levy, constituting a complex effect from both the income and expenditure sides. Given the fundamental role of energy in an economy, the short-term effects of a carbon tax will eventually ripple throughout the economy with possibly surprising outcomes [22,37]. In the long run, the reduction activities in company may bring long-term benefits as taxing carbon can push firms to reduce energy consumption and associate costs through low-carbon technology innovation and

[1] On November 30, 2015, the opening day of COP21 (the 21st session of the Conference of the Parties to the United Nations Framework Convention on Climate Change) in Paris, the Carbon Pricing Leadership Coalition (CPLC) was officially launched with the goal of the initiative to advance effective carbon pollution pricing systems and expand their use globally. Ahead of the Paris climate talks, a Carbon Pricing Panel was convened by World Bank Group President Jim Yong Kim and the International Monetary Fund's Managing Director Christine Lagarde, and meanwhile joined by OECD Secretary General Angel Gurria, to call on their peers to follow their lead and urge countries and companies around the world to put a price on carbon pollution. And the carbon tax is exactly one of the two main types of carbon pricing [9].

[2] Primary distribution of income depicts how the value generated by the production process is distributed among labor, capital and the government in the form of wages and salaries (labor remuneration), operating surplus/mixed incomes (capital income), and taxes on production [34], namely the distribution of national income among households, enterprises and the government. Redistribution of income refers to the regular transfers between institutions/sectors through taxes, government expenditures and social security system, etc. [35].

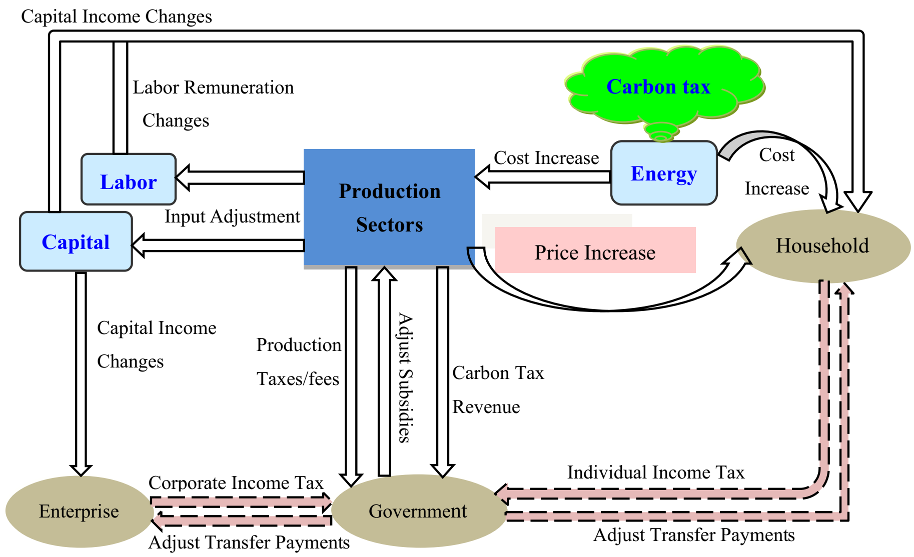

Fig. 1. Schematic diagram of the transmission mechanisms of a carbon tax in the short run. (Solid lines indicate the effects transmitted in the primary income distribution and dotted lines represent those in the redistribution of income.)

installation, thus the company may become more competitive in the market [38,39]. For households, carbon mitigation activities can improve the environment quality and mitigate the adverse impact of climate change thus can bring long-term environmental benefits to human beings. A grasp of the transmission mechanism of the effect caused by carbon taxation can help to better understand its distributional impacts and further categorize them.

The distributional effect of a carbon tax is very complex and influenced by many factors. These factors may include household consumption patterns, production structures of enterprises and competition between them, distribution of co-benefits from improved environment quality, and the carbon tax design.[3] Among these factors, the carbon tax design, especially the use of the carbon tax revenues is frequently regarded as a key point to affect or even alter the result of a tax's policy performance [40,41].

The carbon tax design includes a number of important factors, each of which has implications in terms of effectiveness and distribution: who should pay the tax, what should be taxed, how much is the tax rate, when to impose the tax, the use of tax revenue (also called preferential policy design), and how to enforce the tax. From the practical experience of countries that have introduced a carbon tax, along with studies introducing and modeling a hypothetic carbon tax, we can see that the design of a carbon tax system differs from country to country. In general, the taxpayers are enterprises and households, but in some cases certain types of households and enterprises can be exempt from a direct tax levy; the tax base contains fossil fuels in both primary and secondary energy sources, although most studies suggest only taxing primary energy to avoid a double levy. There often exist "upstream" or "downstream" choices in the energy chain to impose the tax [42]. The tax rates among countries often vary over a wide range; for example, in 2015, it ranges from a less than $1/t$CO_2$ in Mexico and Poland to a high tax rate of $130/t CO_2 in Sweden [14]. These can be based on what is perceived as politically feasible [22], or based on the marginal abatement cost of carbon [43], or simply by budget requirements [44].

[3] Besides these factors, how the carbon tax is modeled and which indicators are chosen will also impact the resulting distributional effects of a carbon tax. We summarized these methodology (see Table SI1) and indicators (see Table SI2) and provided them in the Supplementary materials of this paper.

Indeed, the assessment on the effect of a carbon tax is always based on a specific tax design. A carbon tax can generate additional revenue for the government, and the tax design—especially the use of its revenues—will directly affect its environmental effectiveness and socio-economic impacts. Here we do not intend to provide a detailed description of every element of the carbon tax design but instead to focus on the use of the tax revenue. From the existing practices of carbon taxation we find that the introduction of a carbon tax is usually accompanied by preferential policies. For example, Norway taxed the paper industry at a half rate and exempted shipping and aviation [45]; Sweden increased the levy on energy products but reduced the income tax rate [11], and meanwhile set the carbon tax rate of the production sectors to be only 25% of the household sector's rate [45]; Denmark's energy intensive sectors could enjoy a lower tax rate than other sectors if they committed to reduce emissions, and all of the carbon tax revenues paid by each sector could be recycled back to the respective sector as labor subsidies or energy saving investment [45]. Therefore, before reviewing the distributional impact of carbon tax, it is necessary to summarize the corresponding preferential measures and exceptions.

Methods employed to alleviate the potential adverse distributional effect of a carbon tax can be categorized into (1) ex-ante measures, which aim to relieve the most vulnerable groups through lower tax rates or exemptions; and (2) ex-post measures, compensating groups that are most affected through reducing other distortionary tax or increasing transfer payments [11]. These two approaches are sometimes combined to complement each other and to achieve tax neutrality, i.e. to keep the government share the same. See Table 1 for a summary:

Overall, these preferential measures can cushion the potential negative impacts of a carbon tax to some extent. However, every design has its advantages and disadvantages and may also perform differently under different circumstances. In general, ex-ante measures such as exempting or lowering the tax rate for specific sectors (mainly energy-intensive industries) could reduce the negative impacts on the economy and enhance the political acceptability, but at the same time will decrease the environmental effectiveness [15]. Directly recycling the carbon tax revenue to households either through a lump sum or direct transfers/subsidies could help alleviate the potential regressivity of a carbon tax or even convert to a progressive carbon tax. However, some authors

Table 1
Categories of preferential measures associated with the carbon tax.

Categories	Measures	Descriptions and applications
Ex-ante measures	Exemptions	For energy intensive sectors [24]; or household sectors [13,22]
	Differential tax rates or tax abatement	Tax abatement for individual/specific sectors [45]; energy consumption could be taxed only above a certain floor so that each household has a tax-free energy allowance [4,12]
Ex-post measures	Reduction of other distortionary taxes	Lowing labor tax [102–104], income tax [22,23,37,49,65], commodity tax [80], production tax [22,89], consumption tax [23,89], VAT (Value Added Tax) [62,88] and sales tax [85], etc.; as well as using as distortionary tax swap/shift [63,70]
	Compensation measures - recycle the carbon tax revenue to households/ production sectors through transfer payments and subsidies	A lump-sum redistribution of fiscal revenues to populations/taxpayers/households [18,22,23,37,66,77,102,103]; improving social security system/increasing social welfare [49,65,104]; increasing existing social transfers [85], food subsidies [84] and public transport subsidies [62], etc. increasing social benefits to low income groups [29,63,105]; subsidizing energy saving measures for industrial sectors [106]

see these compensatory designs as inferior to reducing a distortionary tax because the latter is seen as being more efficient in offsetting the negative impact on GDP growth and employment [46], thus a trade-off between efficiency and fairness often exists in designing the use of carbon tax revenues [12]. A comprehensive tax design might do better in considering both of these issues simultaneously. For instance, applying carbon tax revenue to reduce the indirect tax rate while increasing public transfer payments to vulnerable/low-income households will help narrow income inequality and minimize the negative impacts on the economic system [22,29]. However, this would also increase the government's administrative costs when implementing such a carbon tax in practice. It is hard to devise a generally optimal carbon tax design, but one feasible approach for the government would be to first choose a preference design based on its own social situation and policy priorities and then to adjust the policy design according to its existing performances [47].

3. Results and discussion on distributional impacts of carbon taxation

With the early introduction of the policy in Nordic countries in the 1990s, carbon taxes began to attract researchers' attention and relevant studies began to spring up. One important aspect of such studies involves an evaluation of the distributional impacts across household groups. For example, Pearson and Smith [48] and Poterba [27] both proposed that a carbon tax is regressive, meaning that the cost of a carbon tax, in terms of share of income, on low income households is heavier than it is on high income households. Later on, there were intensive debates on the issue of whether the carbon tax is regressive or not [49–54], leading to numerous studies. Among the numerous studies, we found that besides the distributional concerns across households, many researchers also pay attention to the distributional issues across production sectors. Through reviewing these studies, we got some findings in terms of the distributional issues within households and across economic sectors, respectively.

3.1. Distributional impact of taxing carbon across household groups

Baranzini et al. [4] suggested that the distributional impact of a carbon tax among households can be measured across different dimensions, e.g., among households over various income groups, between rural and urban households, among different household types, and among different generations, which can be shown in Table 2.

Different consumption preferences and patterns will lead to differences in the carbon tax burden experienced by various income groups. Low income groups tend to consume more on energy-intensive products for their basic needs and have limited substitution possibilities and thus, they might bear a relatively higher carbon tax burden. Studies then shift their attention to the distributional effects along other dimensions than income, such as differences in family types, locations, demographic differences, and intergenerational distribution. One important reason is that household characteristics such as type of housing, car ownership, employment and commuting patterns are important factors affecting the distributions of CO_2 emissions [55,56] and thus the important determinants of the effects of the tax on households. Overall, most studies focus exclusively on the distributional impacts among income groups and only recently added other dimensions as new data is coming online.

IPCC [10] notes that it is important to calculate the total cost of mitigation over the entire lifetime of a policy; and one common practice is to use the discount rate when comparing costs over time. The discount rate is a crucial factor in the context of a cost-benefit analysis of the intergenerational equity of mitigation policies. There has been plenty of literature discussing the problem of setting an appropriate discount rate[4] [10,57]. However, the issue of the discount rate itself is complex and subjects to a high level of uncertainty. Many studies focus on modeling the discount rate but sadly, unanimous and reliable conclusions have not been drawn. Stern [57] indicated that most current models make two flawed assumptions related to the discount rate: (1) people will be much wealthier in the future; and (2) that lives in the future are less important than current lives. However, this issue is beyond the framework of this review, here we only mention that the big problem of discounting remains a matter of dispute and that the application of discounting to estimate specific polices such as carbon or GHG taxes is lacking. Considering that addressing climate change requires multigenerational efforts and affects the well-being of future generations, studies on the intergenerational distributional impact of carbon tax or other mitigation policies is really a gap with an urgent need to be filled. Meanwhile, Dennig et al. [58] suggested that the intraregional economic inequalities related to the social cost of carbon are as significant to the optimal carbon price as the debate between Stern and Nordhaus on discounting, indicating a need to strengthen studies of regional inequalities.

In addition to being classified according to their various dimensions, existing studies can also be categorized into carbon taxes in

[4] Discounting is a mathematical operation making monetary (or other) amounts received or expended at different times (years) comparable across time. The discounter uses a fixed or possibly time-varying discount rate (>0) from year to year that makes future value worth less today [10]. Discounting is used to translate future costs to current dollars. The high discount rates that predominate essentially assume that benefits to people in the future are much less important than benefits today [57].

Table 2
Distributional impacts of the carbon tax for households.

Household segmentation	Countries/regions	Common conclusions for each category of studies
Among income groups	Denmark [13]; the US [53,63,64,68]; the Netherlands [43]; Ireland [49,65]; the UK [67]; France [66]; China [29]; Cyprus [107]; Sweden [62]; Taiwan [108]; Shanghai [79]; Singapore [105]; Spain [55]	The carbon tax is regressive or exacerbates inequities
	New Zealand [59]; Italy [60]	The carbon tax is neutral for Italy [60], or neither strictly regressive or progressive in New Zealand [59]
	Italy [61]; Spain [109]; SRB (Susquehanna River Basin) in the US [37]; China [77]; British Columbia [110]; Australia [23]; Vietnam [105]	The carbon tax shows progressivity
	Canada [51]; Indonesia, Malaysia, the Philippines and Thailand [105]	A non-monotonic (U-shaped) relationship occurs between carbon taxes and inequality/income
Between urban and rural households	Ireland [49]; China [22,29]; the UK [67]; France [66]; Indonesia, the Philippines and Thailand [105]	Rural (and suburban) households have higher tax burdens or welfare losses than urban households
	Denmark [13]; four provinces in Canada [73]	No significant differences exist between families living in rural and urban areas
	Cyprus [107]; Malaysia [105]	Urban households are more affected than the rural households
Among households from different regions	*International:* European carbon taxes [111]; Global carbon taxes [17,112,113]	Higher tax burdens fall onto poorer countries
	Regions within a country: The US (into 9 regions) [63]; Sweden (into 3 types of regions: big, middle and sparsely populated areas) [103]; China (into 30 provinces) [114]; four provinces in Canada [73]	Carbon tax incidence across regions might be modest in the US [63] or significant in China and Canada [73,114]; and in Sweden, households living in sparsely populated areas were the most affected [103]
Among households grouped by other demographic characteristics	*Household size:* Denmark [13]; Ireland [49]; Cyprus [107]; Spain [88]	Larger families were less affected than smaller families
	Socio-economic status: The UK [67]	Disadvantaged families were more affected due to having fewer options to buy low carbon alternatives
Among generations	[12,115–117]	Carbon mitigation might induce an uneven distribution of cost/benefit across current and future generation; and also between the younger and older generations coexisting at a given date

developed and developing countries, respectively. This categorization leads to the following findings:

(1) Most studies that focus on developed countries show that the carbon tax is regressive.

Most studies on the distributional impact of carbon taxes focus on developed countries. Although several studies show that taxing carbon in certain developed countries/regions might be neutral (e.g., New Zealand [59], Italy [60]) or weakly progressive (e.g., Italy [61], SRB in US [37], Australia [23]), more studies show that the carbon tax in developed countries is regressive (e.g., Denmark [13], Sweden [62], the US [63,64], the Netherlands [43], Ireland [49,65], France [66], the UK [67], etc.), which is consistent with the IPCC [10] indicating that the impacts of national carbon taxes on consumers would likely be somewhat regressive in high-income countries. For example, Callan et al. [49] demonstrated that the absolute weekly carbon tax payment for the richest households in Ireland is only 37% more than that of the poorest households, whereas the disposable income of the richest households is eight times that of the poorest. Hassett et al. [53] showed that the additional cost of a carbon tax in the US is approximately 3.7% for the lowest decile, which is over four times the added burden of the highest decile. Similarly, Bureau [66] found that the poorest households in the Paris region lose 6.3‰ of their income compared to 1.9‰ for the wealthiest, demonstrating that the carbon tax is regressive before revenue recycling.

The primary reason for the regressivity of carbon tax in developed countries lies in that the proportion of income in spending on fossil fuels decreases with the income levels; in other words, lower income households shoulder a higher carbon tax burden [13,53,68,69]. However, these studies also show that the extent of the regressivity is weak and also depends on the choice of assessment indicators. For example, if lifetime income but not annual income was chosen for measurement, the regressivity would be weakened [53,70–72]; the selection of income or expenditure to measure the relative cost may also affect the result [73,74]. Another interesting finding is that when distinguishing between domestic energy (cooking, heating and lighting, etc.) and transport fuels, the carbon tax burdens attributable to domestic energy consumption tend to be regressive, whereas those to the transport fuels are weakly progressive [4,12,75]. New evidence for 21 OECD countries also shows different distributional effects of energy taxes by energy carrier. Some countries show progressive effects of taxes on transport fuels, whereas others either experience more proportional effects or tend to place the highest burden on middle expenditure deciles; taxes on heating fuels are slightly regressive, whereas taxes on electricity are more regressive [74]. Therefore, Büchs and Schnepf [76] emphasized that assessment of the fairness implications related to mitigation policies need to be measured for separate emissions domains.

(2) Quantitative studies focused on the distributional effects of carbon tax in developing countries have not yet yielded a consistent conclusion.

With a few exceptions, the studies on the distributional implication of a carbon tax in developing countries have only recently begun and are still inconsistent in drawing a general conclusion. Some studies suggested that household consumption patterns in developing countries are significantly different from those of the industrialized countries; for example, the ownership and use of motor vehicles in developing countries tend to be more concentrated in high income families, and a large amount of traditional biomass energy has been used in rural areas, etc. Thus, the performance of a carbon tax in developing countries is not consistent with that in developed countries [77].

OECD [69] quoted an early study by Shah and Larsen [78] showing that a carbon tax in Pakistan could be progressive. Based on this empirical research, OECD [69] found that the net effect of a carbon tax in developing countries could well be proportional to income, or even progressive, when all relevant shifts are taken into account [11]. However, later quantitative studies do not support this conclusion. In China, Brenner et al. [77] found that introducing carbon charges would have a progressive impact, whereas Liang and Wei [22] and Liang et al. [29] found that taxing carbon would widen the urban-rural gap and have an overall regressive result. Jiang and Shao [79] also found that a carbon tax in Shanghai would have a comprehensive regressive distributional effect. In Indonesia, Yusuf and Resosudarmo [80] found not only that a carbon tax favors factors that are more proportionately endowed by rural and lower income households but also that their expenditures are less sensitive to the prices of energy-related commodities, thus making the carbon tax not necessarily regressive. However, another of those authors' studies, addressing fuel price reform [81] in Indonesia, showed that although an increase in vehicle fuel prices could lead to a progressive result, it tends to increase inequality especially in urban areas when the price of domestic fuel (kerosene) also increases. Agostini and Jiménez [82] found the distributional incidence of a gasoline tax in Chile is slightly or moderately progressive, whereas an earlier study on environmental taxes in Chile found that the SO_2 and NO_2 taxation tends to be slightly regressive [83]. In Mexico, Gonzalez [84] found that the costs of a carbon tax are distributed regressively when the revenue is recycled as a manufacturing tax cut and distributed progressively when it is recycled as a food subsidy. In South Africa, Alton et al. [85] found that using carbon tax revenues to lower sales taxes is almost distributional neutral; using them to reduce corporate taxes is more regressive; and using them to expand social transfers (based on current allocations) leads to strongly progressive welfare outcomes. Datta [86] examine the incidence of fuel taxation in India and found that it would be progressive, whereas Blackman et al. [87] found that a 10% fuel price hike in Costa Rica through direct spending on gasoline would be progressive, its effect through spending on diesel would be regressive and through spending on goods other than fuel and bus transportation would be very slightly regressive, thus rendering the overall effect neutral and modest.

In sum, as noted in Section 2, regardless of a country's development status, the design of the carbon tax with respect to how the tax is implemented and how its revenue is recycled could effectively weaken or eliminate its initial regressive or progressive effect in either developed or developing countries. Therefore, some researchers propose that the distributional concerns should not necessarily prevent carbon mitigation [40,73] because the policy design—especially the use of revenue—would have a strong influence on the distributional impacts of the tax [41] and there are ample opportunities for the country to adjust tax and benefit schedules to alter the overall incidence [40].

3.2. Distributional impact of taxing carbon across production sectors

When discussing distributional impacts of a carbon tax, the focus is usually on impacts on households but not on production sectors. Indeed, as mentioned in Section 2, production sectors will suffer short-term and long-term impacts incurred by a carbon tax. Due to differences in the input structure and price elasticity of products, these effects will be differentially distributed across production sectors thus might lead to uneven impacts across sectors.

Intuitively, the extent of the effect of taxing carbon would vary with the proportion of fossil fuel consumed during production, indicating that larger users of fossil-based energy would be more strongly impacted in the short run [37]. Existing studies generally support this conclusion. For example, Oladosu and Rose [37] suggested that the introduction of a carbon tax in the SRB of the US will have the most prominent effects on the output of energy sector in both the short- and long-run, and the highest output reductions are for coal, crude oil, petroleum products, and electricity. Labandeira et al. [88] found that an energy tax reform in Spain will have uneven effects across economic sectors; production activity in energy-intensive sectors would be reduced significantly, leading to considerable increases in their prices. Alton et al. [85] showed that the employment in the carbon-intensive mining sector suffers the most under a carbon tax in South Africa. Liu and Lu [89] showed that a carbon tax in China would negatively shock the output of most sectors proportional to their emissions intensity, i.e. carbon-intensive industries would suffer the most. In addition, not only the carbon tax but also the cap-and-trade mechanisms have such potential uneven distributional effect across sectors [90,91]. A difference is that the allocation method of emissions allowance is a main factor that influences the sectoral distributional effect of cap-and-trade [92].

Energy-intensive industries often receive specific exemptions in carbon tax system. For example, Norway applied a high tax rate to the offshore oil and gas industry, whereas certain industrial processes are exempt [15]. Sweden initially imposed a similar rate on households and industry in 1991 but then reduced the industry rate to 25% of the household rate in 1993, and later increased again to 50% in 1996; and it is now automatically adjusted according to the inflation rate [15]. Denmark has a comparatively complicated three-tier system of tax rates for industry which consists of one standard rate and three reduced rates for energy-intensive processes combined with agreements on energy savings [15], etc. However, just as mentioned in Section 2, ex-ante measures are very likely to decrease the emissions reduction effectiveness of a carbon tax. Therefore, given that a national carbon tax may shock energy-related industries and hence GDP in the short run, the government always chooses to implement preferential measures to protect these industries. Instead of pure ex-ante protection measures like tax rate cut or exemption, we recommend that the policy design should focus on providing incentives for them to reduce emissions by low-carbon technology innovation and replacing the backward technologies in the long run. This can be realized through a direct investment or subsidy to the advanced technology or an ear-marked fund (which means that carbon tax revenues are in advance allocated to finance specific environmental programs) [4]. Such a special protection mechanism should be phased-out in the long run.

Finally, we have to mention that attentions paid to the distributional issues across industries are far less than those to the households. Existing results are too general to provide practical policy recommendations. When simulating the distributional issues across industries, the differences in their regional location, production scales, and long-term benefits should be considered for they are all factors affecting the evaluation results. The coordination of carbon reduction and renewable energy support policies should also be taken into consideration due to their interactions and overlapping objectives [93]. Moreover, for both taxes and trading, if non-CO_2 GHG emissions which are currently exempted will be included, significant changes will occur in the distribution of costs and benefits across sectors [94]. Such a system will be more cost-effective [67] and more preferred by sectors [94], but will meanwhile face the difficulties with monitoring and control [94].

3.3. A discussion of the loophole of existing assessment on distributional issues

Mitigation can have many potential co-benefits and adverse side-effects, including effects on a partly overlapping set of objectives such as local emissions reductions and related health and ecosystem impacts, biodiversity conservation, water availability, energy and food security, energy access, income distribution, efficiency of the taxation system, labor supply and employment, urban sprawl, and the sustainability of the growth of developing countries [10]. A most direct one is its environmental co-benefit. For the whole society, carbon mitigation can correspondingly reduce the pollution and damage to the environment and ecosystem [39,95], thus could bring the short-term and long-term benefits for human health and a better living environment. These environmental benefits include both the global level, such as to help mitigate global climate change so as to avoid sea level rise and extreme weather, etc.; and the local level such as reducing local air pollutants such as SO_2, NO_X and PM 2.5 and other types of environmental pollution [39,95–97]. The local level benefit may not be evenly distributed across regions due to an intuitive sense that the heavily polluted areas will benefit the first and most from a national level carbon tax; and even the global level effect can have different impacts on different areas (e.g., on coastal areas via sea level rise) [10]. Therefore, the distribution of the effect of a carbon tax, in terms of cost and benefit, might be uneven [4,31].

However, existing studies on the distributional impact of carbon taxes usually focus on the distribution of its cost only, but there are only few studies that quantitatively evaluate the distribution of its environmental co-benefit. Such an absence occurs not only in the carbon or GHG taxation but also among other mitigation policies. IPCC [10] also pointed out that the estimates of the macroeconomic cost of mitigation usually represent direct mitigation costs and do not take into account the co-benefits or adverse side-effects of mitigation actions; these costs are only those of mitigation without capturing the benefits of reducing CO_2eq concentrations and limiting climate change. The ignorance of those environmental benefits in assessing the distributional impact will not only overstate the emissions abatement cost but may also have an influence on the distributional impact of such a tax [95–97]. This is due to a fact that poor households/workers are usually more likely to be exposed to pollutants and less able to be protected from the pollution detriment, thus may benefit the most from the improvement of environment quality. This loophole, to date, still has not been well-addressed in existing studies. However, it is worth to note that a few recent studies began to pay attention to qualifying the uneven distribution of the environmental co-benefit of carbon mitigation across regions/provinces [96,97], but a more detailed level of assessment across various income or other socio-economic groups is still lacking.

4. Conclusions and policy implications

The Paris climate conference (COP21) reached the first-ever universal, legally binding global climate agreement which establishes a long-term goal to hold the increase in global average temperature to well below 2 °C above pre-industrial levels by the end of this century [98]. Such a goal cannot be realized without the implementation of climate actions in each of the 195 countries. However, one of the major issues hindering the adoption of climate actions in a country/region is the distributional concern [4,27]. Climate actions/policies involve costs and benefits related to both industries and households thus would be a matter of great concern to them. This study pays special attention to the distributional issues of climate polices, aiming to clarify that if such polices will cause uneven distributional effects to a country, how to comprehensively assess the distributional impacts and how to design an optimal policy to avoid the adverse distributional effects, etc. Among various climate policies, this study focuses on carbon taxation, not only because it is one of the two most popular carbon pricing mechanisms, but also because the distributional issue of carbon taxes has attracted worldwide attentions and been continuously heatedly debated during the past 2–3 decades. Although some countries have already introduced a carbon tax or carbon emissions trading system, most countries are still hesitant to take actions or currently remain in a cautious wait-and-see attitude. A better understanding of the distributional issues of carbon taxes can help alleviate people's fear of such a policy and promote its policy acceptance. Up to now, the distributional effect of carbon taxation has spawned a productive research agenda. Through reviewing these studies, we obtained the following findings.

Existing studies on the distributional impact of taxing carbon can be classified into two main categories, i.e., within households and across production sectors. Studies have estimated the distributional impact within households from multiple perspectives. Overall, these studies mainly focus on developed countries and conclude that a carbon tax tends to be regressive but to a rather weak extent. While for developing countries, the relatively fewer studies fail to support a consistent conclusion that a carbon tax is either regressive or progressive. Thus, more studies on developing countries are still needed to help those countries make clear whether or not carbon mitigation would aggravate problems related to income distribution. Studies paying attention to distributional issue across production sectors are not as common as those on households but overall show that the higher proportion of fossil-fuel based energy a sector consumes, the more adverse impact it will suffer from a national uniform carbon tax. Although this will encourage low-carbon technology innovation/ green economy transition through more expensive fossil fuels, a shock to energy-related industries could also ripple throughout the economy and lead to a temporary decline to GDP growth and employment which might lead to resistance especially from well-organized lobbying groups of potentially affected companies. One key to the solution lies in the carbon tax design. Ex-ante and ex-post measures are used to alleviate the negative impact of a carbon tax. Generally, ex-ante measures through exempting or lowering their tax rate can enhance the policy acceptability by these protected sectors, but meanwhile weaken its effectiveness [15]. Ex-post measures through directly recycling the carbon tax revenue to households can mitigate the potential regressivity of a carbon tax, but may also be inferior to the distortionary tax cut designs in terms of economic efficiency [46]. Trade-offs between efficiency and equity always exist in designing a carbon tax.

Nevertheless, a shortcoming is found in existing quantitative studies, which lies in the ignorance of the distribution of the environmental benefits/co-benefits created by a carbon tax. This ignorance may not only overrate the economic cost but also shift the distributional impact of such a tax. Moreover, a GHG taxation including all GHG emissions are estimated to be more cost-effective and more equally distributed than a tax on CO_2 alone [67]. For this case, we recommend that the design and the implementation of climate mitigation should take into consideration other domestic political priorities and policy measures. For developing countries, and especially emerging economies such as China and India, which contribute a large part of global GHG emissions and at the same time suffer urgent and severe air pollution problems, the mitigation policy should not only focus on CO_2 emissions and other GHG but look for potential win–win opportunities across policy arenas such as the dual effect of green urban areas on mitigation, urban amenity values, public health outcomes and improvements in air pollution control (see e.g. [99,100]). Following this argument, the assessment on the distributional impacts of these mitigation measures should incorporate the distribution of environmental co-benefits rather than just the cost. Such a more comprehensive assessment would better show the cost-effectiveness and distributional impacts and thus enhance the public acceptance of such mitigation policies in these countries. In addition, the revenue of a carbon or GHG tax could be used to either amplify the effect of the tax through subsidies for renewables and low-carbon technology [55,67,101] or an ear-marked fund to environmental programs [4], and/or ameliorate negative side effects by using the tax revenue to mitigate "fuel poverty" through funding retrofitting of houses [67] or transfer payments for low-income families [29,63]. Moreover, ex-post evaluation on the policy performance with regards to economic, environmental and distributional impacts provides important information for the government and the public about the effectiveness and fairness of these measures as well as provides important considerations for countries which have not yet implemented a carbon tax or other carbon policies.

Other suggestions relate mainly to future research work. First, methodologies still need to be improved (please see the Supplementary materials). Second, more deep-going research dimensions/perspectives are still in need on the design of the carbon tax and its distributional effects within households and across production sectors. For within households, the research dimensions should be expanded among households characterized by detailed demographic characteristics such as age, occupation, family type and size, etc. For across production sectors, attention should be paid from not just a short-term but a long-term perspective. More importantly, the distributional concerns across regions and generations must be enhanced for both households and industries. Comprehensive studying from detailed perspectives/dimensions could help to obtain specific and practical carbon tax designs for policymakers. This may also involve another problem of data availability and data reliability; therefore, we recommend that detailed survey and questionnaires can be conducted to complement the deficiencies in the statistical data.

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Appendix A. Supplementary material

Supplementary material associated with a summary of methodologies and indicators for evaluating the distributional effects of carbon taxes are provided in the online version, at http://dx.doi.org/10.1016/j.apenergy.2016.06.083.

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