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Estimating the target-consistent carbon price for electricity

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Economists have a marked preference for taxes and subsidies as instruments to correct externalities like greenhouse gas emissions or learning-by-doing spill-overs, while policy makers are clearly more attracted to quotas and targets despite their risk of inefficient allocations. Targets have clear political attractions in encouraging agreement between nation states. The 2015 COP 21 Paris Agreement on climate change set ambitious targets for 2050 that have been translated into "nationally determined contributions" by each of the 196 Parties. The EU requires Member States to publish *National Energy and Climate Change* plans while the UK Government has legally binding carbon budgets.

Crucially, target setting addresses the club goods problem of financing public goods. The EU's *20-20-20 Directive* set target shares of renewable energy for each Member State, ensuring that each county jointly financed the club good of the learning-by-doing spill-overs. In addition, targets are more credible and durable than carbon taxes. Uncertainty about future carbon prices increases investment risk (and its cost) and encourages delays. Finally, targets provide the necessary coordination of the supply chains needed to deliver the investments required to meet the targets, as has been dramatically demonstrated in the GB Offshore Wind Industry.

Policy-makers nevertheless need a shadow price of carbon (SPC) for cost-benefit analysis if they are to make efficient choices within and across different sectors of the economy. Ideally this would be the social cost of carbon (SCC), the present discounted value of the marginal damage of releasing one tonne of CO_2. However, the methodology used to calculate the SCC is highly sensitive to a large number of imperfectly known parameters and assumptions. Instead it is more useful to estimate a target-consistent carbon price, where the target, at least at a high level, derives from the Paris Agreement devolved down to nation states, and within each, to sectoral levels. The UK Government calculates a target-consistent shadow carbon price for sectors not subject to the Emissions Trading System carbon price and publishes targets for decarbonizing the electricity sector.

The route to rapid decarbonization invariably starts with decarbonizing electricity, first, because the technology exists and is cost-competitive while requiring no change in the final product (and hence no need for behavioural change), and second, electrification is the route to decarbonizing sectors such as transport, heating and industrial processes. Clearly that only makes sense if the electricity itself has been decarbonized. While there is a powerful case for target setting, there remains a strong case for calculating the shadow carbon price (SPC) for each target. Significantly different SPCs imply that the choice of targets will not be least-cost.

Given its key role, this paper sets out a method for calculating the target-consistent carbon price for the electricity sector, illustrated for the island of Ireland (which has a challenging renewables target). For most countries decarbonizing electricity requires a massive increase in Variable Renewable Electricity (VRE, e.g. wind and solar PV). The problem is that the ratio of peak to average on-shore wind can be 3-4:1, and even in the most favourable sites and offshore, at least 2:1. In northern European counties solar PV has ratios of 8+:1. The share of VRE in total annual generation will be limited by its average capacity factor (i.e. the fraction of full operating hours per year, 25%-33% for most on-shore wind, 10%-13% for PV). At high VRE penetration (e.g. above 50%) peak output will exceed total demand (including exports and storage), and the resulting surplus must be curtailed (i.e. spilled or wasted). When it comes to calculating the target-consistent carbon price for such systems, this paper argues that a quite different approach is needed from the normal approach based on the carbon intensity of different generating technologies.

The key insight is that *marginal* curtailment is typically more than three times *average* curtailment, so the contribution of each additional MW of VRE will displace less and less carbon from the fossil generation needed to maintain system reliability and capacity adequacy. The standard approach to choosing the least-cost technology mix assumes that each technology is controllable and so the main question is balancing capital and operating (mainly fuel and carbon) costs to meet variable demand. High-capital low-operating cost plant should run on base load (i.e. almost all the time) while the infrequent peak demands are best met with low-capital high-operating cost plant as in standard screening curve analysis. This standard approach breaks down once VRE reaches the point at which it is necessary or economic to curtail excess generation, and a different approach is needed to compute both the efficient plant mix and, the subject of this paper, the shadow price of carbon.

The paper shows that the SPC in electricity can be derived from the marginal curtailment formula. The key concept is residual demand, that is, domestic demand less VRE output. When this becomes negative, the surplus VRE can either be stored (if there is spare storage capacity), exported (if neighbouring countries are able to accept increased imports), or will have to be curtailed. In addition to these hourly varying state variables, the System Operator will need to maintain adequate fast-acting flexible capacity to maintain system stability and reliability, in ways that impose additional constraints on the volume of VRE that can be accepted.

The higher is VRE penetration, the higher will be the average curtailment factor, while the marginal curtailment of adding more VRE capacity will be 3+ times this average factor. The carbon displaced per MW of extra VRE will be the carbon-intensity of the displaced fossil generation in tonnes CO_2/MWh, times the capacity factor of this last, marginal, MW of VRE. Given the costs of adding VRE and the cost saving from displacing fossil generation, the cost per tonne of CO_2 abated then gives the shadow price of carbon, SPC, which increases, possibly sharply, with increased VRE penetration.

The paper develops a simple model to gain greater insights into the relationship between VRE penetration and the shadow price of carbon, which in turn should clarify the target-consistent carbon price for electricity. The simple model illustrates the magnitude of the SPC and its dependence on ways of mitigating curtailment. An important practical question is whether the last few increments of decarbonization result in a sharp increase in the SPC, in which case it may be better to adjust targets (and delay complete electricity decarbonization) to equalize target-consistent carbon prices across sectors.