Varieties of low-emissions innovation[*]

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Abstract

Climate change mitigation will require the transformation of modern energy systems. That transformation will in turn require significant advances in technologies for energy production, distribution, and use; and the regulatory and organizational structures that shape technology adoption. This paper examines whether the link between economic institutions and innovation, posited by the Varieties of Capitalism literature, holds for so-called "green innovation". It finds little evidence of systematic variation between LME and CME economies for either innovation inputs or comparative advantage outputs. Furthermore, it reviews a range of confounding explanations for success at low-emissions innovation that complicate inference about institutional determinants of low-emissions innovative success. Finally, it proposes an alternative explanation grounded in domestic energy policy and legacy structure of domestic energy systems.

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1 Introduction

Long-term emissions reduction will necessitate an array of changes to how advanced industrial societies produce, distribute, and use energy. Managing these changes successfully will require substantial innovation to improve low- and zero-emissions energy technology, incorporate it in legacy power systems, manage the inherent intermittency renewable energy brings with it, and improve end user efficiency.

While the climate problem has motivated interest in these innovations, the economic opportunities in low-emissions technology now command significant attention. The European Union has explicitly cited competitiveness in energy technologies as a motivating factor for its energy policy.(The European Commission, 2006, 2010) The WTO has become a battleground for international disputes over renewable energy production.(Bradsher, 2010; Scott, 2010) Finally, the notion of "green growth", in which emissions mitigation would generate growth-enhancing technological and industrial change, has been warmly received (OECD, 2011), despite the its many shortcomings (Huberty et al., 2011).

This paper examines comparative rates of success at low-emissions technological innovation in the industrialized countries. In contrast to the Varieties of Capitalism tradition, it argues that low-emissions innovation will not, primarily, depend on macro-institutional frameworks of economic governance. Instead, I argue that the nature of a low-emissions energy systems transformation, and the problem of economic change embedded in it, inform against making strong inferences about future success based on institutional ideal types. Rather, I argue that states with successful low-emissions innovation and technology sectors reflect states in which the incentives of the legacy energy system have interacted with the potential for economic change. To the extent that states have been able to maintain long-term commitments and constituencies in favor of low-emissions technological change.

This argument emerges in three stages. I first demonstrate that the appropriate measure of innovation depends on whether one is most concerned with the economic or environmental problem motivating interest in "green" innovation. I then show that, for the purposes of the environmental problem, we see relatively high levels of innovative productivity across most advanced industrial economies. I further show that where relative differences exist, they overlap with and are inseparable from structural features of geography and industrial legacy arguably independent from the macro-institutional environment that features prominently in the VOC literature. I then provide new estimates of the strength of low-emissions innovation and innovation potential across the industrial economies. I argue that this variability owes a great deal to the ability of national governments to use legacy costs and opportunities present in national energy systems to construct durable political coalitions in favor of long-term technological change. I conclude with implications of this argument for both green growth and environmental policy.

2 What form of innovation matters?

Low-emissions innovation matters, in related by analytically distinct ways, to two different environmental and economic problems. Environmentally, any viable solution to the emissions problem will require substantial changes in how we produce, distribute, and use energy. That energy systems transformation (Jacobsson and Bergek, 2004; Zysman and Huberty, 2010; Smil, 2011) will require the development of new technologies alongside substantial improvements existing ones. Even with these innovations, serious emissions reduction will, consistent with past transformations (Smil, 1994; Sieferle, 2001), likely require substantial social, political, and economic changes. But the scope of adaptation to new technology pales in comparison to the changes that emissions reduction would require absent radical innovations in renewable energy and energy efficiency.

In that case, achieving emissions goals would require radical reductions in overall energy use. The threat to overall living standards implicit in such a reduction would likely make the task of implementing and sustaining policy impossible. Hence the viability of long-term emissions reduction is inextricably linked to the practicality of new solutions to emissions-free energy.

Political viability links the environmental problem to the second, economic concern. The origins and patterns of low-emissions innovation will influence comparative advantage in a range of capital goods markets. Command of those markets has become a controversial goal since the disappointments of the Copenhagen climate change summit in 2009. The advanced industrial countries appeal to "green growth" in the hope that it will provide a jobs- and growth-generating foundation for reflating their economies (OECD, 2011; Schepelmann et al., 2009; The European Commission, 2006), while the developing economies now see "green" development as a way to pay for environmental protections they are otherwise reluctant to take on.[1] Ensuing disputes with the emerging economies over subsidy and tariff schemes have received intense scrutiny from the WTO.(Bradsher, 2010; Scott, 2010; Woody, 2010) Forecasting the evolution of these markets depends on some concept of national variation in low-emissions innovation systems.

This economic problem is closely tied to the question of politically viable climate policy. "Green growth" hopes to reconcile long-term environmental goals for emissions reduction with the short- and medium-term political and economic mandate for stable and improving living standards. By turning the process of low-emissions innovation to the purposes of job creation and productivity improvements, green growth policies would, if successful, improve long-term policy stability by linking emissions reduction

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[1] Interviews with senior EU climate policy negotiators in 2011 suggested that the Chinese became substantially less difficult negotiating partners as Chinese industry began to excel in green export markets.

to short-term economic prosperity.[2] Consistent with Patashnik (2008), the ability to use environmentally-motivated policy to generate near-term material beneficiaries would substantially improve the likelihood of policy success.

However linked these motivations are, however, they do not lead to the same metrics for measuring innovation. If what we care most about is the climate problem, then pure productivity is the only thing of interest–whether we can generate enough innovation, fast enough, to take emissions out of the energy supply at the pace needed for effective climate change mitigation. This is the perspective of those who argue in favor of China's rapid progress on solar cell manufacturing, for instance: who cares if it may depend on dubious industrial policy practices and heavy-handed, state-sponsored acquisition of intellectual property? What matters, in this instance, is the cost-per-watt.

In practice, of course, this and other examples of rapid state-driven innovation have proven politically contentious because of their effects on high-end capital goods markets. As Huberty et al. (2011) have argued, to the extent that viable "green growth" strategies depend on exports for generating surplus returns, they risk a new "green mercantilism" wherein competition for markets takes on political as well as economic significance. In that case, we then would wish to know if we observe durable or predictable patterns of relative comparative advantage in green innovation and production, and whether or how those patterns map to state policy.

3 Absolute production

Drawing on Dechezleprêtre and Martin (2010), we find relatively little evidence of the Varieties of Capitalism arguments regarding innovation at work in absolute levels of in-

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[2] For a range of case studies about the political nature of green growth policy, see the overview and country studies published for the Green Growth Leaders forum, available at `http://greengrowthleaders.org/knowledge/`.

novative productivity in “green” technologies. Their data show that, for 9 of 19 categories of low-emissions technologies they consider, the top three countries by patent share are the US, Germany, and Japan. In five of the ten remaining categories, the US and a large CME economy (Japan or Germany) are both in the top three. Finally, the share of national innovations in climate-related technologies follows a fairly constant pattern for all economies other than the US: high in the 1970s, declining into the 1980s, and then recovering again after 1990. Indeed, what emerges is a pattern by which the major economies are major producers of low-emission innovation, with the US as an occasional outlier.

These data also show (figure 1) that the so-called liberal market economies underproduce “green” innovation relative to either GDP or overall innovative activity. To a first approximation, this would appear to confirm the general VOC innovation hypothesis. Much of the innovation associated with low-emissions technologies consists of marginal improvements to well-known technologies: larger and more efficient wind turbines, higher-yield solar cells, cheaper manufacturing processes for solar cells, more efficient building materials, and so on. To the extent that the LME/CME dichotomy maps onto a radical/incremental innovation dichotomy, the relatively greater specialization in low-emissions technologies among the CME economies appears unsurprising.

Here, however, a number of important caveats are in order. The LME economies share a variety of structural differences that have significant effects on energy markets but are arguably unrelated to the problem of firm coordination that motivates the VOC framework. The LME economies are, in general, younger, geographically larger more likely to have substantial carbon-intensive energy resources, more likely to have low population density (figure 7) consequence of their significant geographic size, and more likely to have extensive suburbs that generate structural disincentives towards mass transportation. Furthermore, while the core Coordinated Market Economies all import substantial quantities of energy for electricity production (figure 8), the LME economies by and large have large domestic coal reserves and depend on imported energy largely for transportation. The recent discovery of shale gas, and economically viable techniques to extract oil from tar sands, have only exacerbated this difference.

Thus while the LME economies appear to under-perform the CME and Scandinavian economies in the production of “green” innovation, their reasons for doing so are arguably over-determined. The demand-pull features of LME energy systems are shaped by a variety of factors only tangentially related to the macro-institutional structure of those economies. We will return to this point in section 6 for its long-term influence in shaping incentives for low-emissions energy systems transformations and technological innovation.

4 Relative comparative advantage

The VOC hypothesis, of course, is less concerned with absolute advantages and more with relative differences–the origins of diversity in revealed comparative advantage across otherwise equally rich countries. But with low-emissions innovation, we again see substantial diversity of a form not obviously correlated with the VOC hypothesis. This position has substantial support in the literature. Neither Taylor (2004) nor Ahlquist and Breunig (2009) succeed in recovering the VOC country clusters from measures of cross-national innovation.

We calculate relative measures of innovative success as follows. Using the European Patent Office PATSTAT database of cross-national patenting, we aggregate country-level patents by 8-digit IPC code for all years in the period 2000-2009.[3] This constitutes approximately 14 million patents across 135 countries over ten years, in nearly 65,000 categories.

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[3] Complete details of the selection method are given in the appendix.

Since patent counts are long-tailed, we use only those categories with more than the median count of 62 patents over 10 years. This leaves approximately 33,000 IPC patent categories in the data set. Using this data, we calculate the revealed technological advantage (RTA) as a measure of country-level specialization in a given innovation domain. Then, following the IPC Green Innovation inventory as prepared by the World Intellectual Property Organization, we categorize RTA values by their relationship to an array of "green" categories ranging from alternative energy to waste treatment and disposal.[4]

In aggregate terms, we observe no substantive difference in the distribution of specialization within "green" patent categories. In aggregate terms, shown in figure 4, we observe little obvious difference in relative patterns of specialization across the advanced industrial economies. Once again, the US appears as an outlier, suggesting that its high level of aggregate productivity does not translate into higher relative specialization in "green" technologies. Breaking the RTA values down by either the top-level IPC (A-H) categories or the IPC Green Inventory subject matter areas, shown in figure 3, we once again observe little substantive variation.[5]

5 Innovation and trade competition

To this point, we have seen that absolute levels of productivity in "green" innovation favor, unsurprisingly, the large, complex economies of the US, Japan, and Germany; while comparative patterns of revealed technological advantage show relatively little structure to green variation across economies. Furthermore, we've suggested that what differences do exist may be a product of incentives in the legacy energy systems, such as the contin-

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[4] The green inventory contains 827 8-digit IPC codes, assigned to 7 major categories of "green" innovation. More detail is available at `http://www.wipo.int/classifications/ipc/en/est/`

[5] Preliminary cluster analysis, following the methods used by Ahlquist and Breunig (2009), suggests no obvious LME/CME clustering on these patterns of specialization.

ued availability of domestic fossil fuel resources, whose origins are arguably orthogonal to the structure of the domestic macro-institutional environment.

The VOC literature, however, emphasizes revealed comparative advantage rather than innovation for its own sake. This emphasis is closely related to the question of green growth: to the extent that policy sustainability will require emissions reduction to generate economic returns through command of export markets or other forms of efficiency, we should ask whether some institutional environments are more hospitable to linking the technological demands of green innovation to the economic demands of comparative advantage.

The VOC literature provides some reason to believe that CME economies would excel at translating domestic energy and climate policy into comparative advantage. A growing body of literature (Helm et al., 2003; Victor, 2011; Zysman and Huberty, 2010; Huberty, 2012) has argued that emissions pricing may not be politically sustainable, regardless of its economic efficiency. It generates acute costs without generating offsetting benefits, almost guaranteeing highly organized opposition and weak long-term support. This contravenes evidence from literature on policy sustainability (Patashnik, 2008). In contrast, non-market or quasi-market approaches to coordinating changes in the energy system, such as feed-in tariffs, renewable portfolio standards, and other instruments, may offer greater chances of success. Given the VOC emphasis on institutional complementarity and policy success, we may expect that the VOC countries would excel at designing and implementing less market-based mechanisms to incentivize low-emissions innovation and technology adoption, and in turn to comparative advantage in "green" industries.

Linking innovation performance to command of export markets will require a new set of measures. This section presents preliminary results of several new measures. Appendix

A describes the methodology behind these measures and discusses their properties and caveats.[6] Here we discuss three different measures: the degree of specialization in green innovation domains; the intersection of product specialization with innovation specialization across a broad set of potentially "green" goods; and the intersection of product specialization and innovation specialization in the high-profile wind turbine and solar cell industries. As we should in each case, the patterns of specialization that emerge do not immediately reflect the canonical VOC clusterings. Rather, as section 6 will argue, they reflect the degree to which states have successfully used green technologies to either solve costly problems in their legacy energy systems, or capture economic opportunity.

5.1 Specialization in "green" innovation

While we observe little aggregate difference in RTA values across the advanced industrial economies, this does not simultaneously equate to different levels of aggregate specialization in green innovation writ large. Figure 6 provides two measures of specialization, discussed in detail in appendix A.5. Two surprising details stand out from the bottom panel. First, in aggregate terms, a subset of CME and Scandinavian countries appear more specialized in green innovation than the bulk of the LME economies, excepting Canada. In particular, Germany, Austria, and the Netherlands excel at a broader spectrum of green technology than the rest of the CME economies and all LME economies.

Second, a handful of not obviously "green" economies display specialization in at least as wide a range of innovation domains as the best CME economies. China, Russia, and Poland all do very well in aggregate measures of green innovation. Part of this, of course, is due to their greater emphasis on heavy manufacturing, which features heavily in the green innovation inventory in the form of boiler, engine, and chemical engineering

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[6] These measures and others are currently under development, in concert with an ongoing project with Georg Zachmann at Bruegel.

innovations.

Figure 4 breaks this down further for the VOC economies. We again observe little consistency across categories. For alternative energy production in particular, we continue to observe mix of CME and LME economies at the top of the specialization ranking. The one place where the CME / LME dichotomy appears to hold is in transport, where the canonical CME economies Germany and Austria far outrank everyone else.

Specialization in green innovation does not, per se, translate into command of green export markets. Instead, it only signals the possibility of an innovation system capable of translating advances in a range of technologies into products competitive on world markets. To account for this, the top panel in figure 6 also attempts to identify "green" production specialization in relation to green innovation. Here, we see a greater diversity of countries at the top ranks of "green" producers: the LME, CME, and Scandinavian economies are intermingled together in the ranking, while China and Poland do well in production as well as innovation. But the comparison of the top and bottom panels in figure 6 makes clear that success at green innovation is only partially correlated with success at establishing competitive international manufacturing industries. Furthermore, the ability to pull of that translation is not obviously correlated with the categorization of production systems as "liberal" or "coordinated".

5.2 Evidence from two industries: wind and solar production

Section 5.1 used a broad definition of "green" production, consequence of the difficulty of identifying green products within the HS-6 product classification. Some technologies, however, can be directly identified in the trade data. In particular, wind turbines (HS-6 code 850231) and solar cells (HS-6 code 854140) stand out for both the general interest in their markets and their importance to a low-emissions energy systems transformation.

Figure 6 provides evidence, using measures defined in section A.3, of the innovation performance of countries that specialize in these two industries worldwide.

We observe a few stylized facts:

- Countries that specialize in wind turbine production and export appear to excel at fewer "related" innovation categories than is the case for solar cells
- The most competitive country in wind turbines (Denmark, for whom wind turbines constitute 10% of all exports) actually patents quite little in turbine-related technologies
- Solar cells show much broader innovative specialization, with little distinction in overall activity among the LME, CME, and Scandinavian economies

6 Varieties of low-emissions innovation?

The data presented to date cast some doubt on the proposition that macro-institutional differences in the advanced industrial economies have generated substantive variation in the degree or kind of "green" innovation and production. Instead, we see significant diversity both within and between institutional arrangements. This diversity persists whether we prioritize absolute levels of innovation, the degree of "green" innovative specialization across countries, the degree of specialization in goods with a minimum green innovation content, or the innovative performance in narrowly identified "green" goods like wind turbines or solar cells..

This should, we argue, come as little surprise, for two reasons. First, as noted in section 3, the sources of variation in national energy policy are influenced, at least in part, by structural features of those markets closely correlated with, but arguably not caused by, the CME/LME dichotomy. The VOC provides no underlying rationale for why this variation should occur. That the US, Australia, and Canada have large domestic fossil fuel resources and low-density populations may or may not influence their choice of labor market, capital, and welfare state institutions. At the very least, any theory linking these features would have to account for the relatively dense, geographically constrained, resource-limited United Kingdom.

Second, the energy sector differs in important ways from the the modal sector with which the VOC framework concerns itself. As a theory of firm coordination, the VOC framework assumes a firm that faces a series of decisions about how to raise capital, where to invest in product development, and how to attract and nurture talent. On the margins, the theory assumes that the differential incentives provided to both employers and workers by economic and welfare state institutions lead to a bifurcation in firm behavior and economic outcomes.

The energy sector looks very different. Particularly in the case of energy carriers, firms produce highly homogeneous products–electricity or chemical energy–with the same general processes. These firms operate in highly regulated sectors in which capital requirements and capital acquisition receive intense scrutiny. The investment needs are relatively homogeneous based on the structure of energy demand, because of the nature of modern energy systems and energy technology.[7] Finally, particularly for the electricity sector, firms' primary focus is on the short- and long-term stability of the system, rather than on technological innovation or competition for new customers. By extension, these firms' demands for new technologies are based less on capabilities or potential improvements

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[7] That is, most modern energy systems use centralized generation, long-distance high-voltage distribution, and constant or average-cost pricing. Hughes (1979) provides reasons to believe that the nature of alternating-current generation provided powerful constraints on the kinds of energy systems imaginable; while Todd (1989) provides evidence from Germany to the effect that the adoption of alternating current technology cemented in place certain forms of regulatory and political organization.

or features, and more on the overriding long-term interest in (and regulatory incentives for) the operating stability of the energy system. Finally, the very long-term capital depreciation cycle of the energy sector deprives it of the natural turnover that helps drive the demand for technological progress elsewhere in the economy.

Low-emissions energy adoption reinforces these sectoral features. At present, and for the foreseeable future, low-emissions energy offers few obvious advantages to energy system operators compared with fossil fuels.(Zysman and Huberty, 2011) Instead, its physical properties often require expensive modifications to the power grid to buffer the system against the inherent intermittency of wind or solar power. Hence, on the margin, utilities will adopt renewable energy only insofar as it either fulfills a regulatory requirement for doing so, or to the extent that consumers demand it and are willing to help pay the cost. This suggests that the market for renewable energy technology today and in the near future is almost entirely a function of policy.[8]

These characteristics imply that the primary drivers for innovative success in renewable energy and low-emissions technology will depend on the ability of states to institute and sustain a long-term transformation of their energy systems. The ability to do so, moreover, appears only weakly correlated with the structure and function of labor market and welfare state institutions. Rather, it will depend on the ability of national and regional governments to stabilize long-term climate policy by linking it to other changes in the energy system that either solve lingering problems created by that system, generate new opportunities from changing that system, or both.

The canonical VOC countries of the United States and Germany provide a pointed example of this problem. Germany, among the world leaders in both domestic renew-

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[8] Market history appears to confirm this pattern. The Danish wind industry faced severe hardship after California suspended its near-term renewable energy programs. Danish firms also had to rely on foreign market demand to sustain them through the 2001-2007 period of renewable energy policy stagnation in Denmark.(Meyer, 2004)

able energy deployment and innovation, imports significant quantites of energy for both transport and electricity production. External supply risks have intensified since 2000, particularly as natural gas supplies from Russia have become subject to ongoing Russia-Ukraine political disputes that yielded five major supply disruptions between 2000-2010. For unrelated reasons, Germany has been unable to expand its use of nuclear energy, and after the Fukushima incident in Japan committed to a long-term abandonment of its remaining nuclear capacity. These features, as Jacobsson and Lauber (2006) have argued, supported political shifts inside the German government that favor long-term renewable energy adoption. Renewable energy both generates domestic, secure energy supplies and supports German industrial manufacturing and labor market stabilization. The former feature provides tangible benefits to a broad swath of industrial and residential energy consumers, while the latter generates substantial benefits for well-defined constituencies.

Constrast this with the United States, which continues to rely on substantial domestic coal and gas reserves for electricity production, has relatively weak domestic capital goods manufacturing firms, and is exposed to energy insecurity only in the transport fuels sector. The US has displayed relatively little federal enthusiasm for renewable energy, not least because doing so would provide few solutions to the external energy security problem. Indeed, a true energy security solution for the American auto sector might well lead to electric automobiles powered from highly efficient coal- or gas-fired power plants. Thus the structural features of the German economy that have helped fuel enthusiasm for the development and deployment of low-emissions technologies are in many cases missing from the US context; and the origins of those differences are orthogonal to the macro-institutional structure of labor and capital market organization.

Thus the features of the energy sector mean that low-emissions innovation will depend quite acutely on the ability of state policy, rather than market institutions, to change sectoral incentives for technology adoption. Its ability to do so, however, depends on whether those changes serve more immediate economic goals than long-term emissions reduction. That, in turn, will depend on whether renewable energy can help solve pre-existing problems created by legacy energy systems for the domestic economy, and in doing so generate near-term benefits that incentivize policy formation and stability.

7 Conclusions

The data presented here lead to a set of stylized conclusions that should inform future research:

- The notion of "green" innovation is a misnomer. Just as Huberty and Zachmann (2011) suggested the incoherence of the idea of a "green" product sector, so to have we shown here that innovations labeled "green" constitute a highly diverse set of technological domains.
- The conventional VOC breakdown of innovators into "radical" and "incremental" does not provide much traction on the question of which countries or national innovation systems succeed at "green" innovation
- Instead, much of the variation in innovation and production excellence across industrial economies appears to derive from the interaction of domestic economic policy and the structure of legacy energy systems

Making progress on the question of who will succeed at green innovation will thus need to go beyond the problem of macro-structural institutional variance, to investigate both why states would embark on a low-emissions energy systems transformation on the one hand, and how they would sustain that transformation in the face of few near-term material benefits on the other. That, we argue, will depend on whether such a transformation permits countries to yoke progress on emissions to progress on other problems created by legacy energy systems. If true, however, this would anticipate a world of diverse approaches to incentivizing low-emissions innovation, and a highly varied climate policy environment in which first-best solutions like emissions pricing are only one among many industrial policies.

Appendices

A The product-innovation space

Formally, consider a set of countries C that trade in a set of goods G and innovate in a set of domains I. Following Hidalgo et al. (2007), we construct two matrices R_G and R_I for Revealed Comparative Advantage and Revealed Technical Advantage, respectively. Bound together, we construct a matrix of dimensions $C \times (G + I)$. Here, G and I have become "outputs" $\omega \in \Omega$ (either innovation or trade outputs) of country $c \in C$. From this output matrix, we construct a joint proximity matrix M, as the set of conditional pairwise probabilities $P(\omega_i > \epsilon | \omega_j > \epsilon)$; that is, the ratio of the number of countries in C that excel in "output" i given that they also excel in output j. That proximity matrix M is now a square matrix of dimension $G + I$.

M is a block matrix with four distinct square blocks:

1. The block PP of dimension $(1 : G, 1 : G)$ is the product proximity matrix, giving the pairwise proximities $P(G_i | G_j)$.
2. The block II of dimension $(G + 1 : G + I, G + 1 : G + I)$ is the innovation proximity

matrix, giving the pairwise proximities $P(I_i|I_j)$.

3. The off-diagonal IP block $(G+1:G+I, 1:G)$ is the product:innovation proximity matrix, for proximities $P(I_i|G_j)$
4. The off-diagonal PI block $(1:G, G+1:G+I)$ is the innovation:product proximity matrix, for proximities $P(G_i|I_j)$

From the revealed advantage matrices and the block proximity matrix PI, we can define a series of country-level measures of innovative diversity, intensity, innovative specialization, and joint specialization in goods and goods-related innovation.

A.1 Innovative diversity

We define the innovative diversity D_C of an economy C as $D_C = \sum_i RTA_{i,C} > 1$, the count of IPC patent categories I for which $RTA_I > 1$. D_C implicitly represents the diversity of innovation occurring in an economy regardless of size. A definition of green specialization can be built atop this definition by restricting I to only in those innovation domains that occur in the IPC Green Inventory.

A.2 Innovative intensity of a good

For a good G in the block matrix PI, we define the innovative intensity ι_G of a good G as $\iota_G = \sum_i PI[G,i] > \phi$: the count of innovations $i \in I$ within a proximity threshold ϕ of that good. We hypothesize that goods that depend on a larger variety of innovations will have higher intensity measures than more basic goods.

A.3 Good-innovation specialization

For a country C, we define its innovative specialization $\sigma_{C,G}$ in a good G for which it has comparative advantage as $\sigma_{C,G} = \frac{\sum_i RTA_{C,i} > 1 | PI[G,i] > \phi}{\sum_i PI[G,i] > \phi}$: the share of innovations i within proximity ϕ of G in which C has comparative advantage.

Green innovation specialization can be defined as a subset of good-innovation specialization such that the innovations I are only those that occur in the IPC Green Inventory.

A.4 Coupling of innovation to production

We assume that producing a good G requires access to certain innovations I. We posit three stylized state types: one which generates innovations at home and produces products drawing on those innovations; one that innovates at home but produces abroad; and one that produces at home with technologies imported from abroad. These ideal types suggest a continuum of innovation-production coupling from tightly coupled to weakly coupled, with weak coupling reflecting either the decision to innovate at home but produce abroad; or produce domestically with imported technologies.

To measure the degree of coupling between innovation and production, we require two measures: one which measures the good-innovation coupling; and one which measures the innovation-good coupling. We note that these are not necessarily symmetric.

To define the coupling from innovation to production, We define the innovative intensity of an economy as the mean maximum proximity between goods G for which the economy has $RCA_G > 1$, to innovations I in which that economy as $RTA_I > 1$. Calculating the innovative coupling of an economy can thus occur according to the following rubric:

```
for country:
    for exports:
```

```
    if RCA_{export} > 1:
        for innovations:
            if RTA_{innovation} > 1
                return proximity
    return max(proximity)
```

A.5 Green specialization

We finally define measures of green specialization in either innovation or production. Specialization in green innovation is defined to be the count of green innovation categories in which a country specializes. The IPC defines 827 8-digit "green" innovation categories within the IPC product code space. We measure overall specialization by counting the number green categories in which a country specializes, where specialization is defined as $RTA_C > 1$.

Green product specialization is more complicated. No good definition of green products exists. Attempts to establish such a categorization have been either highly restrictive (only choosing goods like solar cells or wind turbines that are easily identified in the HS6-level international trade data) or very broad (including steel tubes, since they might be used in the manufacture of boilers).

We instead define "green" production from the data. We treat "green" products as those for which "green" innovations as defined by the IPC constitute, as a share of innovations I within some proximity threshold ϕ, at least 1%. To put this measure in perspective, the maximum innovation content of goods as measured using the metric described in section A.2 approximates 30,000. If all IPC green innovation categories were included in the innovations "proximate" to that product, they would account for approximately 2.5% of the total set of "proximate" innovations. Hence the 1% threshold is conservative in the context of a small set of defined “green” innovation domains. This measure identifies 350 “green” products out of the total set of 5962 HS6 product codes.

Given this definition of “green” products, we then defined “green” production specialization as the share of those green products in which a country specializes.

B Patent selection and counting

We count patents by country and

```
SELECT person.person_ctry_code, IPC.ipc_class_symbol, count(*)
INTO OUTFILE 'ipc_country_count_publn_daterange.txt'
FIELDS TERMINATED BY ',' ENCLOSED BY '"'
LINES TERMINATED BY '\n'
FROM tls211_pat_publn publn
INNER JOIN
      tls201_appln appln
      ON publn.appln_id=appln.appln_ID
      AND appln.appln_kind='A'
      AND publn.publn_date BETWEEN '2000-01-01' AND '2010-01-01'
      AND publn.publn_first_grant=1
LEFT JOIN
     tls207_pers_appln pappln
     ON publn.appln_id=pappln.appln_ID AND pappln.invt_seq_nr=1
LEFT JOIN
     tls206_person person
     ON pappln.person_id=person.person_id
```

```
INNER JOIN tls209_appln_ipc IPC
     ON publn.appln_id=IPC.appln_id AND IPC.ipc_value='I'
GROUP BY person.person_ctry_code, IPC.ipc_class_symbol
ORDER BY NULL;
```

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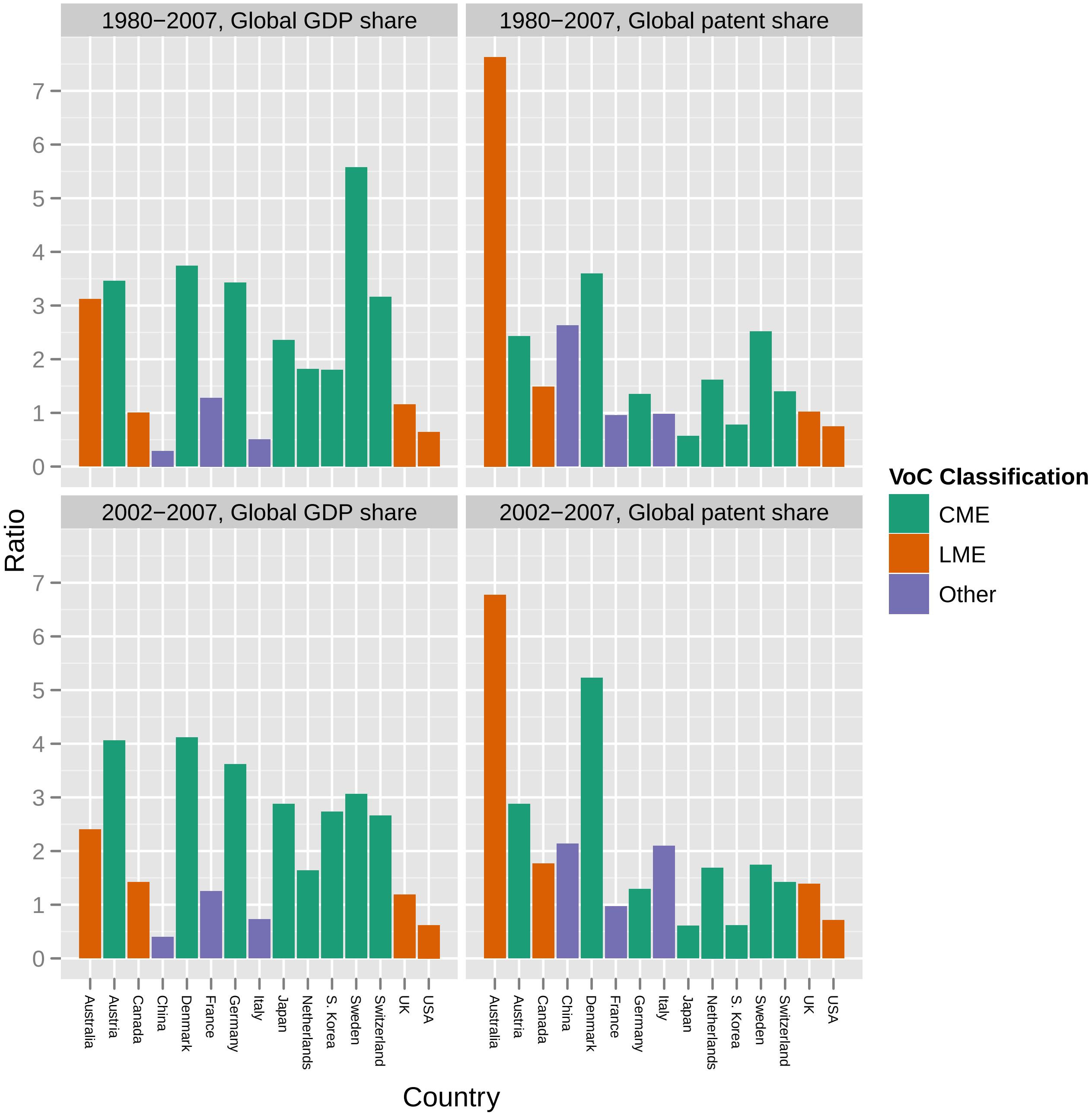

Figure 1: Ratio of low-carbon patent share to share of world GDP and patent filing. Taken from Dechezleprêtre and Martin (2010).

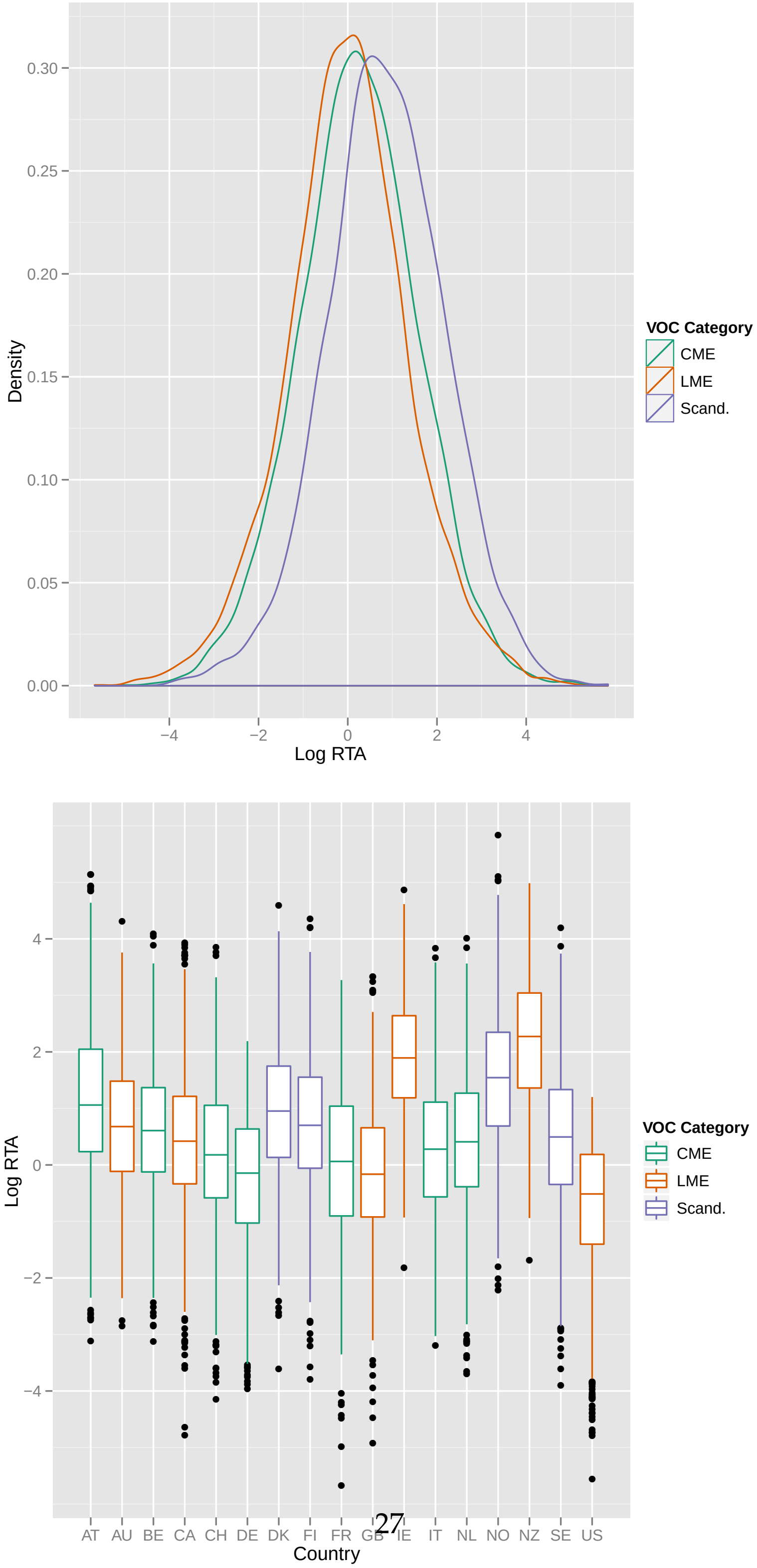

Figure 2: Comparative RTA values across countries and VOC categories, for all patent activity in the IPC Green Inventory. All data from the EPO PATSTAT file for January 1 2000 - January 1 2010.

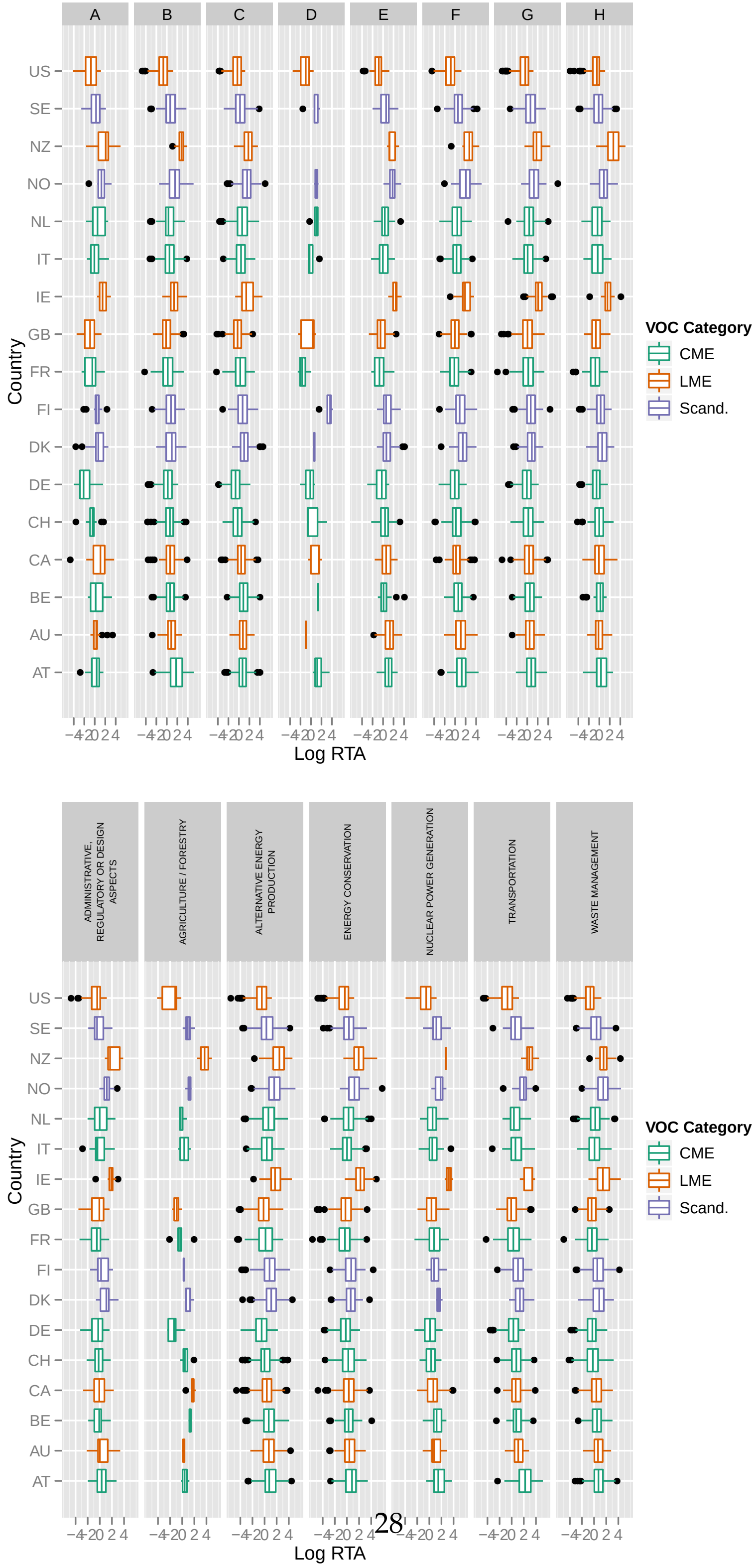

Figure 3: Comparative RTA values by IPC code and green innovation category.

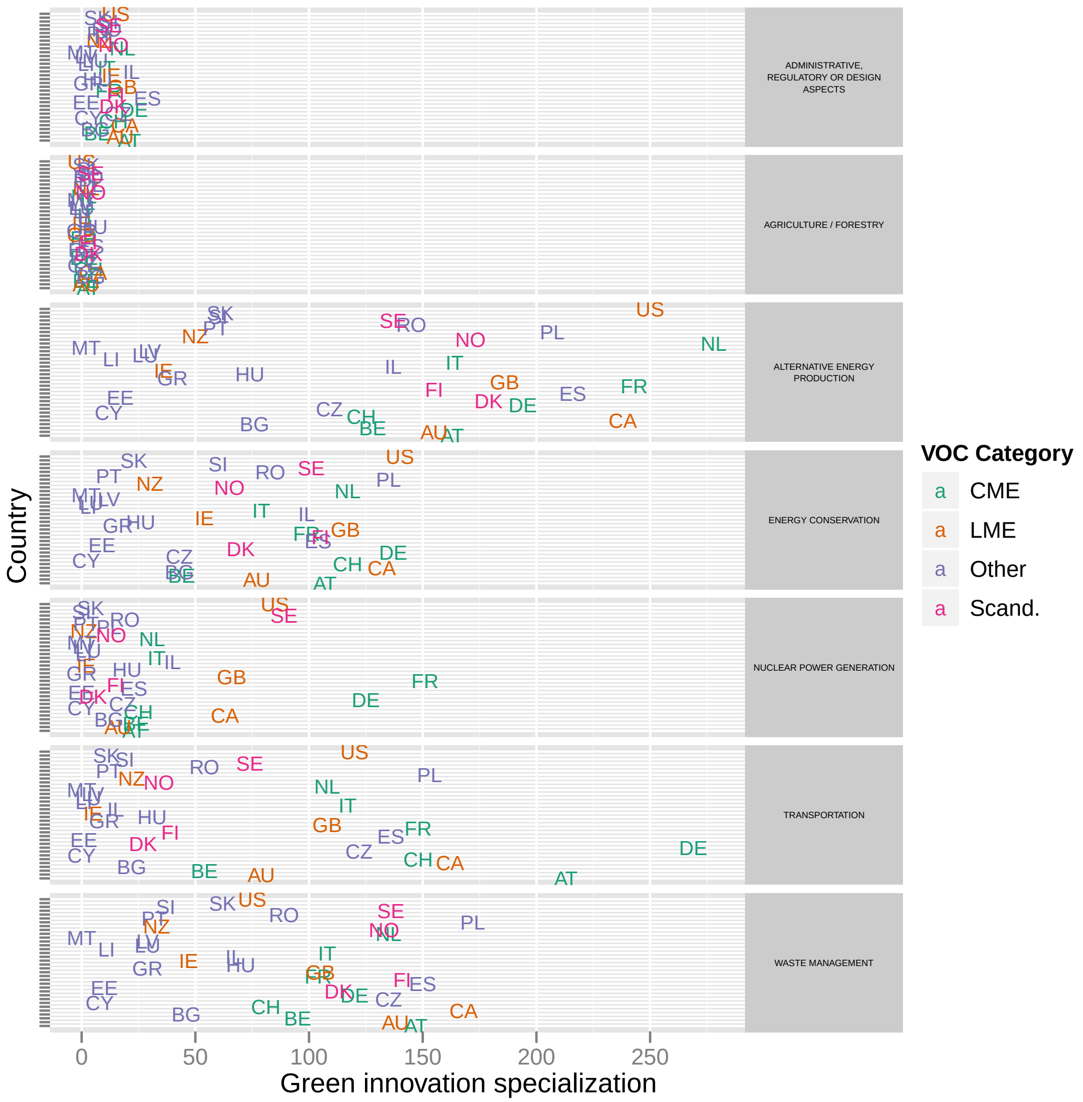

Figure 4: Country-level specialization in "green" innovation categories within the IPC Green Inventory. Patent data taken from the PATSTAT global patent database for January 1, 2000 - January 1, 2010.

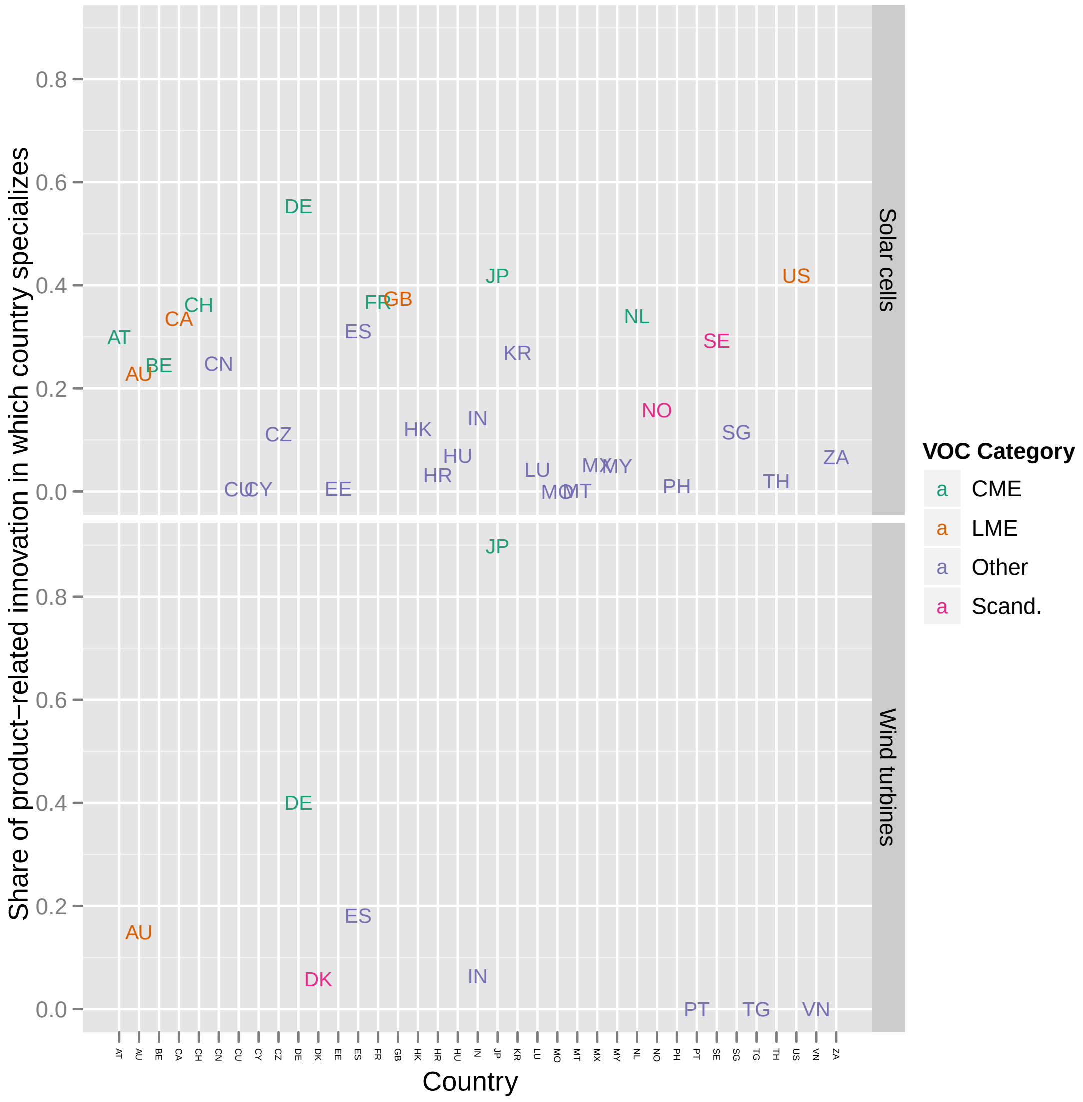

Figure 5: Innovation specialization by country for production in two low-emissions energy goods. Innovative content defined as the share of innovations proximate to the good in question, defined as innovations within proximity $\phi > 0.75$ as discussed in section A.

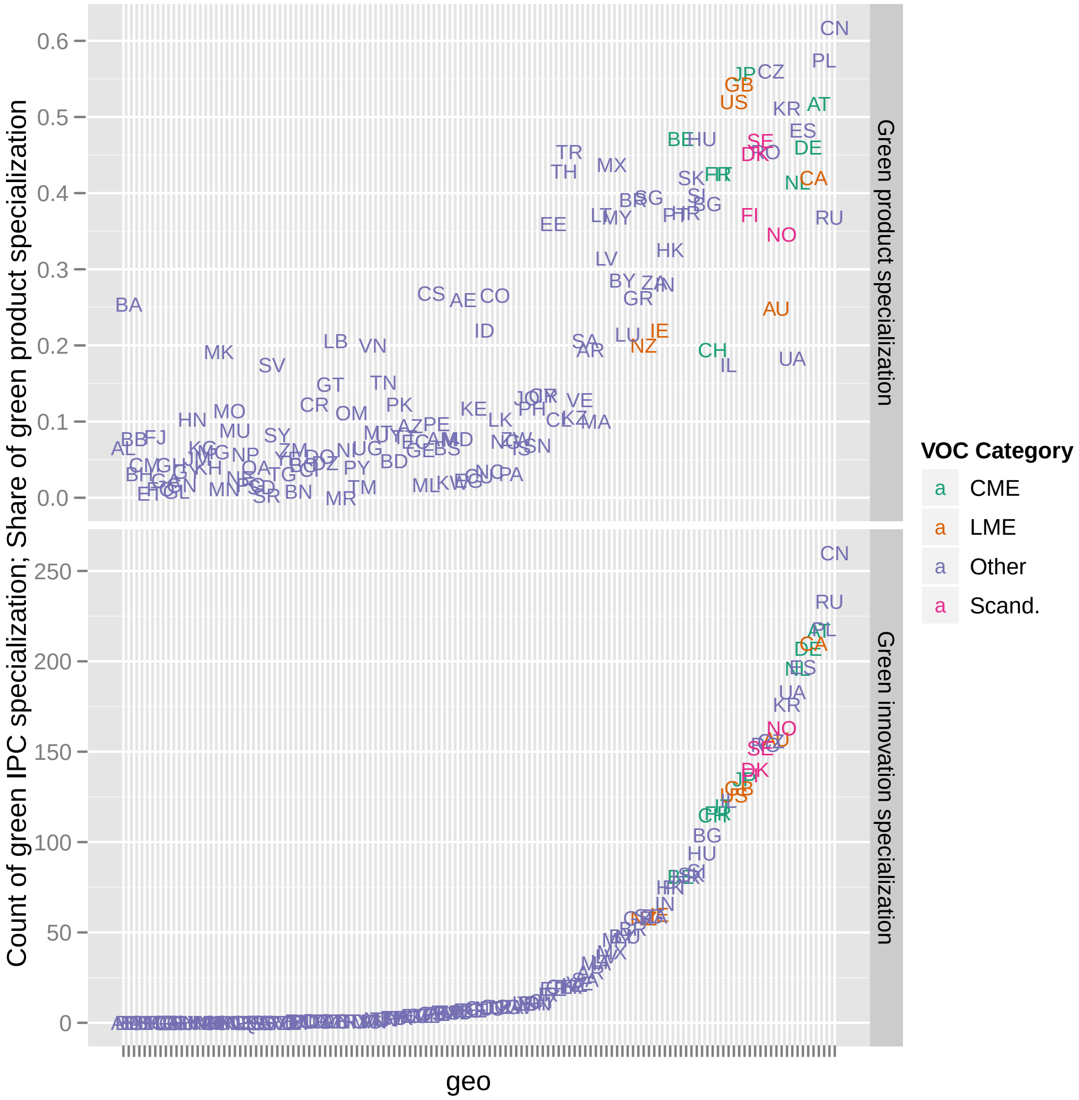

Figure 6: Country performance in "green" production and innovation. Green innovations defined as those IPC codes identified as "green" by the IPC Green Inventory. Green innovative specialization defined as the count of green innovations by country for which $RCA_C > 1$. Green products defined as products for which at least 1% of related innovations occur in the IPC Green Inventory, where "related innovation" is defined as IPC categories with a proximity of 0.75 or greater to the HS-6 product category.

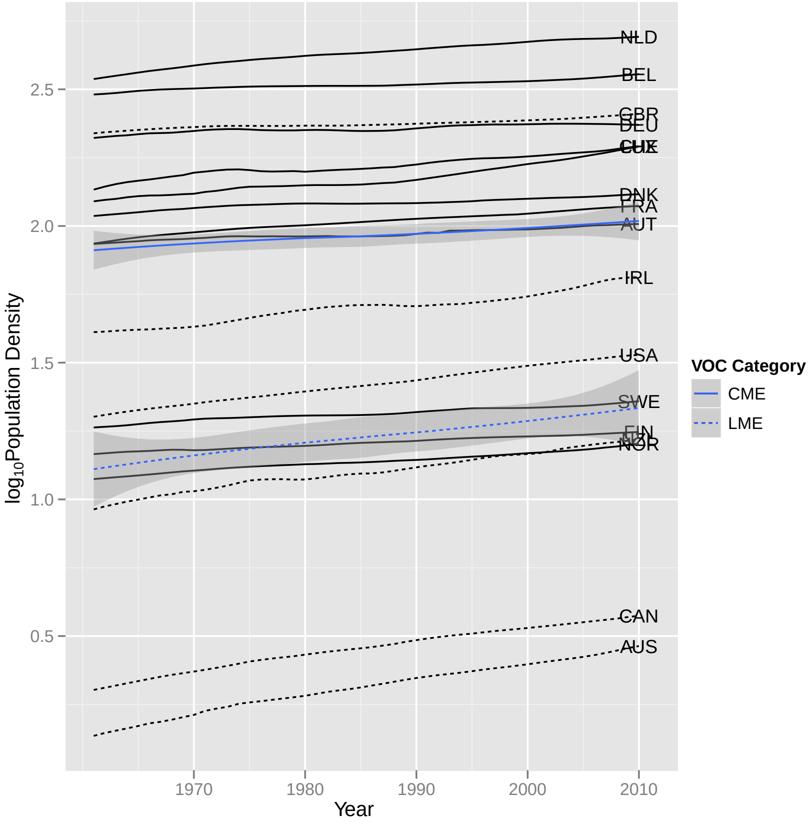

Figure 7: Country and category population density for the VOC economies, 1960-2010. Note that the population densities for the Nordic countries are arguably under-stated, given that most of the population of these countries lives in a handful of cities at the lower latitudes.

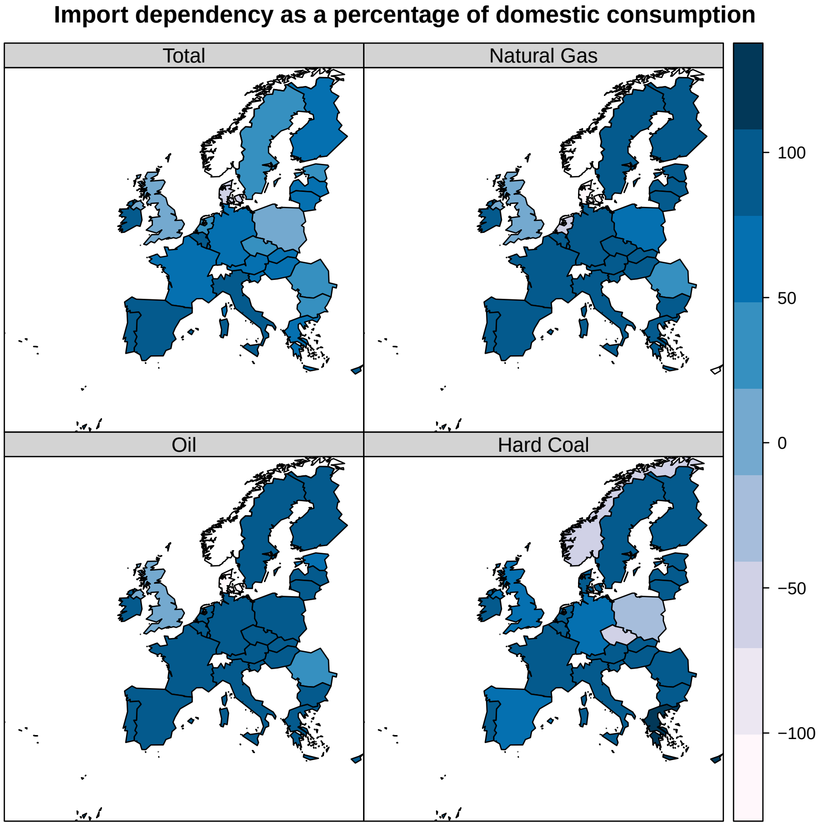

Figure 8: Energy import dependence in the European Union. Note that Norway is omitted from the natural gas, oil, and total categories because its very large fuel exports distort the scale. All data from Eurostat.