Small is Better: The Benefits of *Granularity* in Energy Technologies

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(with Arnulf Grubler, Nuno Bento, Caroline Zimm ...)

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Social Influence and disruptive Low Carbon Innovations

IIASA
“Small is ...” has a long tradition in technology studies, particularly for distributed energy-supply systems.
‘granular’
small unit size
low unit cost
modular
replication

‘lumpy’
large unit size
high unit cost
indivisible
up-scaling
**Granularity metrics**: unit scale vs investment cost

- **Upscaling vs. Modular**

  - Investment cost per unit ($2009)
  - Average unit size (kW)
  - Granularity: granular vs lumpy

- **End-use vs. Supply**

  - Investment cost per unit ($2009)
  - Average unit size (kW)
  - Granularity: granular vs lumpy

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**Unit size and unit cost strongly correlate** in diverse samples of energy supply and end-use technologies.

- End-use tends to be more granular.
- Supply tends to be more lumpy.
Are granular energy technologies ‘better’?

... lower adoption risks?

... more rapid learning rates?

... faster diffusion times?

... lower risks of lock-in?

... more equitably distributed?
Granularity (1): lower adoption effort (investment per unit) results in faster diffusion ($\Delta t$)

35% of variance in $\Delta t$ explained by investment size

NB. two outliers exclude: cars + 2 * WW2
Size matters. Megaprojects carry large risks associated with complexity, one-off designs, and long lead times.

The iron law of megaprojects [Flyvberg 2014]:
“they run over budget, over time, over and over again”

Adoption risks with lumpy technologies:
(i) **bespoke** (non-standard) **design** limits learning;
(ii) complexity, **interdependencies**, interoperability challenges;
(iii) long planning horizons create exposure to **exogenous change**;
(iv) involvement of diverse actors with **competing interests**.

"**policymakers should prefer energy alternatives that require less upfront outlays and that can be built very quickly**“ [Ansar et al. 2013].
Granularity (2): smaller unit sizes & **modularity** result in **lower adoption risk** (% cost overrun)

Size positively correlated with cost overruns in 7 of 9 samples for **up-scaling technologies**
- nuclear
- thermal
- hydro

Size negatively correlated with cost overruns in 4 of 5 samples for **modular technologies**
- wind
- solar

“Some technologies are more open to improvement than others. Compact, modular systems, such as photovoltaics and electronics, are easily experimented on ...”


smaller units
-> more units

-> more opportunities to experiment & learn

-> higher rates of cost reduction

-> more units
Higher learning rates (on average) are associated with standardised production of large number of units.

Learning Rates vs. Cumulative Production

- small n units
  - mean LR ≈ 10%
- large n units
  - mean LR ≈ 20%

nuclear (excluded)
Granularity (3): **more unit numbers enable higher learning rates** (controlling for unit scale economies)

**Learning rates** per doubling of cumulative # of units controlling for **unit economies of scale** (exc. 2 outliers)

\[ y = -0.016\ln(x) + 0.0747 \]

\[ R^2 = 0.49719 \]

-25% -20% -15% -10% -5% 0% 5% 10% 15% 20% 25%

-25\times10^{-4} -2\times10^{-3} -0.1\times10^{-2} -0.01\times10^{-2} 0 -0.01\times10^{-2} 0.01\times10^{-2} 0.1\times10^{-2} \times10^{-1} 1 \times10^{-1} \times10^{0} \times10^{1} \times10^{2} \times10^{3}

granular Average Unit Size (MW) lumpy

unit scale is a stronger predictor of learning rate after controlling for economies of scale

NB. two outliers excluded:
-35% nuclear
+32% geothermal

Granularity (7): **shorter lifetimes** of smaller units enable rapid turnover and reduce **risk of lock-in**

**lock-in** = resistance to change in technological systems

causes:
- technological
- institutional
- behavioural

**granularity:**
- **shorter lifetimes**
- more rapid innovation cycles
Granularity (7): lower complexity (interdependencies) of smaller units further reduce risk of lock-in.

**lock-in** = resistance to change in technological systems

causes:
- technological
- institutional
- behavioural

granularity:
- lower complexity, (as measure of interdependency)

Lorenz curves can describe distribution of **access to useful technologies** (and service infrastructures)

Lorenz curves: distribution of access to technologies

**NB1. includes non-access**

**NB2. not all countries:**

~6bn people

Granularity (8): lower barriers to adoption result in more equitably distributed access to useful services.

Gini coefficient = measure of distributional (in)equality calculated from Lorenz curves

0 = perfect equality
1 = perfect inequality

more granular = lower cost per additional access
In sum: Granularity has many generalizable benefits

- ... lower adoption risks [2]
- ... more rapid learning rates [3]
- ... lower risks of lock-in [7]
- ... faster spatial diffusion [6]
- ... larger market sizes [5]
- ... shorter formative phases [4]
- ... more equitable distribution [8]
- ... higher social legitimacy [10]
- ... greater benefits for system efficiency [9]

Technological characteristics

Adoption environments

Innovation and diffusion processes

System outcomes
But benefits of granularity depend on replication, standardisation ...
But benefits of granularity depend on replication, standardisation ... and access to infrastructure

<table>
<thead>
<tr>
<th>Granularity benefits</th>
<th>Production, manufacturing (standardisation, serialisation)</th>
<th>Installation, adoption (learning, accessibility)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Required conditions</td>
<td>Dominant designs homogeneous producers</td>
<td>Repetitive installation low skill adoption</td>
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<tr>
<td></td>
<td></td>
<td>distributed, modular infrastructure</td>
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<tr>
<td>Potential issues</td>
<td>Experimentation &amp; variety heterogeneous producers</td>
<td>Bespoke installation high skill adoption</td>
</tr>
<tr>
<td></td>
<td></td>
<td>system-wide, lumpy infrastructure</td>
</tr>
</tbody>
</table>

Other more general issues with granularity:
(1) transaction costs; (2) dispersed impacts; (3) lifecycle impacts ...
Granularity is not a hegemonic strategy … but it is too often a marginalised one

Times editorial
1 December 1977

“Dr Schumacher did not advocate smallness as the answer to everything. The title of his book has misled many people. What he was talking about was the appropriate size for different structures – some large, some small. He concentrated only on smallness only to counteract the idolatry of gigantism.”
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