README
"Energy Efficiency and Directed Technical Change: Implications for Climate Change Mitigation"
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Data Availability and Provenance Statement

- All data used in this study are publicly available. A detailed description of all data, including sources and URLs, in Section A of the appendix.
- In addition, all data are provided in the excel file 'Data and Charts.xlsx' included in this documentation. The relevant tabs are to the right of the red tab labeled 'Data -->'.The data in the excel file reflect the version used in this paper. Some of the data may be updated at the underlying source.
- I certify that I, the author of the manuscript, have legitimate access to and permission to use the data used in this manuscript.
- All outputs in the paper can be replicated using the code in this documentation.

Dataset list

- This paper uses data from the `IEA Headline Energy Data' from the International Energy Agency. Accessed 8/5/19 from http://www.iea.org/statistics/topics/energybalances/.[1]
- This paper also uses data from the Annual Energy Review of the Energy Information Administration. Accessed 8/5/19 via https://www.eia.gov/totalenergy/data/annual/.
- This paper also uses data from the State Energy Data System (SEDS) of the Energy Information Administration. Accessed 8/5/19 via https://www.eia.gov/state/seds/seds-data-complete.php.
- This paper uses data from the Performance Curve Database from the Santa Fe Institute. Accessed 8/5/19 via https://pcdb.santafe.edu/index.php.
- This paper also uses data from McGlade and Ekins (2015). The data were accessed on 8/7/19 via https://www.nature.com/articles/nature14016.
- This paper also uses data from the Organization of Economic Development and Control. Accessed 8/6/19 via https://data.oecd.org/rd/gross-domestic-spending-on-r-d.htm.

Computational Requirements

The following software is needed to replicate the results.

- Matlab (code was last run with version 2020b).
    - Dynare (code was last run with version 4.6.2). Dynare can be downloaded from https://www.dynare.org/.
- Stata (code was last run on version SE 17.0).
- Excel: The data organization and creation of several charts was done in the excel file 'Data and Charts.xlsx' included in this documentation.

The code was last run on a 14-core intel-based desktop computer with MacOS version 12.6.

[1] The IEA data have moved and are now available as `World Energy Balances Highlights' at https://www.iea.org/data-and-statistics/data-products. Access now requires registration.

Description of Programs

- Mainfile.m: Main file used to perform all Matlab analyses. Calls all other Matlab files.

- Dynare Files: Mainfile.m calls several Dynare files, which are used to simulate the dynamics of the DTC model.
    - DTC.mod: Dynare file that simulates DTC model with taxes from Cobb-Douglas model (Section 5.1.1) and all rebound analyses (Section 5.2).
        - DTCva.mod: Alternate version of DTC.mod for robustness analyses with exogenous energy prices.
        - DTCconsP: Alternate version of DTC.mod for robustness analyses with constant, exogenous energy prices.

    - Dynare solves the model in intensive form. The Dynare files call the following matlab files to transform the model back out of intensive form and to plot results.
        - GetLevels.m: Transforms Dynare results back out of intensive form.
        - CDcompAnalysis.m: Plots results comparing DTC and Cobb-Douglas models (Section 5.1.1).
        - ReboundAnalysis.m: Plots results for cost-less technology shock (Section 5.2.1).
        - SubsidyAnalysis.m: Plots results for subsidy (Section 5.2.2).
        - TempSubAnalysis.m Plots results for temporary subsidy (appendix section D.4.2).

- The follow files are called by Mainfile.m to calculate least-cost paths.
    - DTC_Objective.m: Objective function for DTC model
    - DTC_Constraint.m: Function that defines constraints for DTC model
    - CD_Objective: Objective function for Cobb-Douglas model

- The following files are called by Mainfile.m and the Dynare files for welfare calculations.
    - LogUtility.m: Calculates lifetime utility under log preferences.
    - CEV.m: Calculates consumption equivalent variation.

- The following files are called by Mainfile.m to conduct the stability analysis in Appendix Section B.7.2.
    - EqR.m: Implicit function for R&D allocations.
    - pTILDEhat.m: Function for dynamics of ptilde.
    - khat.m: Function for dynamics of k.
    - chat.m: Function for dynamics of c.
    - ehat.m: Function for dynamics of e.
    - These functions also call the following sub-functions.
        - gJfunc: Function for technology growth rates.
        - GAMMA.m: Uses implicit function to find R&D allocation.
        - ghat: Function for dynamics of TFP.

Instructions for Replicators

1. Data organization and creation of several figures is done in the Excel file ‘Data and Charts.xlsx.’

2. Run EstimatePsi.do in Stata to recreate the regression results. To run the file, you must first change the default path on line 3.

3. All simulation results can be reproduced using MainFile.m in Matlab. To run this file, you must adjust line 8 to set the default path for all Matlab output and line 9 to identify the location of Dynare.
    a. To reproduce the baseline results, run Mainfile.m after making the path changes described above.
    b. To reproduce robustness results with exogenous energy prices (psi = 0), run Mainfile.m after uncommenting line 54.
    c. To reproduce robustness results with lambda = 0.21, run Mainfile.m after uncommenting line 139. Line 54 should be commented back out.
    d. To reproduce results with psi = 3.64, run Mainfile.m after uncommenting lines 161-163. Line 139 should be commented back out.
    e. To reproduce results with constant energy prices, run Mainfile.m after uncommenting lines 54 and 55. Lines 161-163 should be commented back out.

Details

1. The 'audit' tab in the Excel file 'Data and Charts.xlsx' explains the purpose of each tab. It provides original data sources and how the tabs read from each other. All of the tabs in the 'Charts' section appear in the paper. The audit tab gives the mapping from the excel tabs to figure numbers in the paper. This mapping is also provided in the table below.

2. The Stata dofile 'Run EstimatePsi.do' reads from 'Data and Charts.xlsx'. The results of the analysis are shown in Output/Stata/Costreg.pdf.

3. MainFile.m uses six values calculated in steps 1 and 2, but does not read directly from these files. The relevant values were entered manually.
    - Line 51 in Mainfile.m is the coefficient estimate shown in Output/Stata/Costreg.pdf.
    - Line 83 in Mainfile.m is from Cell B8 in Tab 'Calibration Data' in "Data and Charts.xlsx".
    - Line 84 in Mainfile.m is from Cell B2 in Tab 'Calibration Data' in "Data and Charts.xlsx".
    - Line 85 in Mainfile.m is from Cell B4 in Tab 'Calibration Data' in "Data and Charts.xlsx".
    - Line 86 in Mainfile.m is from Cell C7 in Tab 'Calibration Data' in "Data and Charts.xlsx".
    - Line 87 in Mainfile.m is from Cell C6 in Tab 'Calibration Data' in "Data and Charts.xlsx".
    - Line 93 in Mainfile.m is from Cell H4 in Tab 'Energy Target Calculation' in "Data and Charts.xlsx".

List of Figures/Tables and Programs

The table below maps all of the tables and figures from the paper to the programs included in these replication files. All Matlab and Stata programs are in the folder labeled 'programs'. All output files are within the folder 'Programs/output/'.

Figure/Table #	**Program**	**Line Number**	**Output file**	**Note**
Figure 1a	'Data and Charts.xlsx'		excel/fig1a.png	Tab 'Carbon ID'

Figure 1b	'Data and Charts.xlsx'		excel/fig1b.png	Tab 'Price Comparison'
Figure 2a	'Data and Charts.xlsx'		excel/fig2a.png	Tab 'Expenditure'
Figure 2b	'Data and Charts.xlsx'		excel/fig2b.png	Tab 'Exp Detrended'
Figure 3a	'Data and Charts.xlsx'		excel/fig3a.png	Tab 'Energy Level'
Figure 3b	'Data and Charts.xlsx'		excel/fig3b.png	Tab 'All Resources Final'
Figure 4				Illustration of theoretical results. No data or simulation.
Figure 5				Illustration of theoretical results. No data or simulation.
Table 1	Mainfile.m	51, 83-87, 138, 145-6, 154-7	Matlab/table 1.mat	Values manually copied from matlab output file to latex. See *Instructions to Replicators* for more detail on lines 54 and 86-90.
Figure 6a				Same as Figure 3a
Figure 6b	Stata/EstimatePsi.do	16	Stata/Fig9b.eps	
Figure 7a	CDcompAnalysis.m	57	CDcomp/fig 7a.eps	Baseline results
Figure 7b	CDcompAnalysis.m	65	CDcomp/fig 7b.eps	Baseline results
Figure 7c	CDcompAnalysis.m	73	CDcomp/fig 7c.eps	Baseline results
Figure 7d	CDcompAnalysis.m	82	CDcomp/fig 7d.eps	Baseline results
Figure 8a	Mainfile.m	705	LCP/fig8a.eps	Baseline results
Figure 8b	Mainfile.m	714	LCP/fig8b.eps	Baseline results
Figure 8c	Mainfile.m	723	LCP/fig8c.eps	Baseline results
Figure 8d	Mainfile.m	732	LCP/fig8d.eps	Baseline results
Figure 9a	ReboundAnalysis.m	38	CTS/fig9a.eps	Baseline results

Figure 9b	ReboundAnalysis.m	49	CTS /fig9b.eps	Baseline results
Figure 9c	ReboundAnalysis.m	61	CTS /fig9c.eps	Baseline results
Figure 9d	ReboundAnalysis.m	69	CTS /fig9d.eps	Baseline results
Figure 10a	SubsidyAnalysis.m	38	Subsidy/fig10a.eps	Baseline results
Figure 10b	SubsidyAnalysis.m	49	Subsidy /fig10b.eps	Baseline results
Figure 10c	SubsidyAnalysis.m	61	Subsidy /fig10c.eps	Baseline results
Figure 10d	SubsidyAnalysis.m	69	Subsidy /fig10d.eps	Baseline results
Figure B.1				Illustration of theoretical results. No data or simulation.
Figure B.2				Same as Figure 3
Figure B.3	Mainfile.m	940	Stability/polynomialfit.pdf	Baseline results
Table B1	Mainfile.m	973	stability/stability.mat	Includes results from four runs of Mainfile: Baseline, lambda=0.21, psi=0, psi=3.64. Values manually copied from output file to latex.
Figure B.4				Illustration of theoretical results. No data or simulation.
Figure B.5				Same as Figure 5
Table B2, Column 3	‘Data and Charts.xlsx’			Tab ‘Energy Units’. Cells C12 and C16.
Table B2, Column 3	‘Data and Charts.xlsx’			Tab ‘Primary to Final Conversion’. Cells X11, Y11, Z11.
Figure C.6a	‘Data and Charts.xlsx’		excel/CostResourcePrimary.pdf	Tab ‘Primary Resource Chart’
Figure C.6b	‘Data and Charts.xlsx’		excel/CostResourceFinal.pdf	Tab ‘Final Resource Chart’
Figure C.6c	‘Data and Charts.xlsx’		excel/CostPrimary.pdf	Tab ‘All Resources Primary’

Figure C.6d	'Data and Charts.xlsx'		excel/fig3b.png	Tab 'All Resources Final'
Figure C.7	'Data and Charts.xlsx'		excel/target.pdf	Tab 'Target'
Figure D.8a				Same as Figure 7a
Figure D.8b	Mainfile.m	743	LCP/taxp0.pdf	Baseline Results
Figure D.9a	CDcompAnalysis.m	238	CDcompLong/policy.pdf	Baseline results
Figure D.9b	CDcompAnalysis.m	246	CDcompLong/innovation.pdf	Baseline results
Figure D.9c	CDcompAnalysis.m	254	CDcompLong/E.pdf	Baseline results
Figure D.9d	CDcompAnalysis.m	263	CDcompLong/C.pdf	Baseline results
Figure D.10a	Mainfile.m	869	LCPlong/policy.pdf	Baseline results
Figure D.10b	Mainfile.m	878	LCPlong /innovation.pdf	Baseline results
Figure D.10c	Mainfile.m	887	LCPlong /E.pdf	Baseline results
Figure D.10d	Mainfile.m	896	LCPlong /C.pdf	Baseline results
Figure D.11a	CDcompAnalysis.m	201	CDcomp/LowLambda/policy.pdf	Robustness lambda=0.21
Figure D.11b	CDcompAnalysis.m	209	CDcomp/ LowLambda /innovation.pdf	Robustness lambda=0.21
Figure D.11c	CDcompAnalysis.m	217	CDcomp/ LowLambda /E.pdf	Robustness lambda=0.21
Figure D.11d	CDcompAnalysis.m	226	CDcomp/ LowLambda /C.pdf	Robustness lambda=0.21

Figure D.12a	CDcompAnalysis.m	128	CDcomp/Exprice/policy.pdf	Robustness psi=0
Figure D.12b	CDcompAnalysis.m	136	CDcomp/Exprice/innovation.pdf	Robustness psi=0
Figure D.12c	CDcompAnalysis.m	144	CDcomp/Exprice/E.pdf	Robustness psi=0
Figure D.12d	CDcompAnalysis.m	153	CDcomp/Exprice/C.pdf	Robustness psi=0
Figure D.13a	CDcompAnalysis.m	93	CDcomp/HighPsi/policy.pdf	Robustness psi=3.64
Figure D.13b	CDcompAnalysis.m	101	CDcomp/HighPsi/innovation.pdf	Robustness psi=3.64
Figure D.13c	CDcompAnalysis.m	109	CDcomp/HighPsi/E.pdf	Robustness psi=3.64
Figure D.13d	CDcompAnalysis.m	118	CDcomp/HighPsi/C.pdf	Robustness psi=3.64
Figure D.14a	CDcompAnalysis.m	165	CDcomp/ConsPrice/policy.pdf	Robustness gAV=psi=0
Figure D.14b	CDcompAnalysis.m	173	CDcomp/ConsPrice/innovation.pdf	Robustness gAV=psi=0
Figure D.14c	CDcompAnalysis.m	181	CDcomp/ConsPrice/E.pdf	Robustness gAV=psi=0
Figure D.14d	CDcompAnalysis.m	190	CDcomp/ConsPrice/C.pdf	Robustness gAV=psi=0
Figure D.15a	Mainfile.m	753	LCP/LowLambda/policy.pdf	Robustness lambda=0.21
Figure D.15b	Mainfile.m	761	LCP/LowLambda/innovation.pdf	Robustness lambda=0.21

Figure D.15c	Mainfile.m	770	LCP/ LowLambda /E.pdf	Robustness lambda=0.21
Figure D.15d	Mainfile.m	779	LCP/ LowLambda /C.pdf	Robustness lambda=0.21
Figure D.16a	Mainfile.m	791	LCP/ Exprice/poli cy.pdf	Robustness psi=0
Figure D.16b	Mainfile.m	799	LCP/ Exprice/inn ovation.pdf	Robustness psi=0
Figure D.16c	Mainfile.m	808	LCP/ Exprice/E.p df	Robustness psi=0
Figure D.16d	Mainfile.m	817	LCP/ Exprice/C.p df	Robustness psi=0
Figure D.17a	Mainfile.m	828	LCP/HighPs i/policy.pdf	Robustness psi=3.64
Figure D.17b	Mainfile.m	836	LCP/ HighPsi /innovation. pdf	Robustness psi=3.64
Figure D.17c	Mainfile.m	845	LCP/ HighPsi /E.pdf	Robustness psi=3.64
Figure D.17d	Mainfile.m	854	LCP/ HighPsi /C.pdf	Robustness psi=3.64
Figure D.17a	ReboundAnalysis.m	38	CTS/fig9a.e ps	Robustness psi=0
Figure D.17b	ReboundAnalysis.m	49	CTS /fig9b.eps	Robustness psi=0
Figure D.17c	ReboundAnalysis.m	61	CTS /fig9c.eps	Robustness psi=0
Figure D.17d	ReboundAnalysis.m	69	CTS /fig9d.eps	Robustness psi=0
Figure D.18a	TempSubAnalysis.m	38	TempSub/C. pdf	Baseline Results
Figure D.18b	TempSubAnalysis.m	49	TempSub/R E.pdf	Baseline Results
Figure D.18c	TempSubAnalysis.m	61	TempSub/T FP.pdf	Baseline Results

Figure D.18d	TempSubAnalysis.m	69	TempSub/C.pdf	Baseline Results
Figure D.19a	SubsidyAnalysis.m	38	Subsidy/fig10a.eps	Robustness psi=0
Figure D.19b	SubsidyAnalysis.m	49	Subsidy /fig10b.eps	Robustness psi=0
Figure D.19c	SubsidyAnalysis.m	61	Subsidy /fig10c.eps	Robustness psi=0
Figure D.19d	SubsidyAnalysis.m	69	Subsidy /fig10d.eps	Robustness psi=0

List of Additional Results

A few other numerical results are reported in the paper, but not included in a table. These results are contained in the file 'Matlab/results.mat', which is in the output folder of the replication materials. Below, I provide a mapping between variables in the Matlab output and numbers reported in the paper.

- Section 5.1.1
  - The Cobb-Douglas model misses the target by approximately 12.4 percent. Reported as "CDcomp_miss" in output. Calculated in CDcompAnalysis.m, lines 266-7.
  - Environmental policy in the Cobb-Douglas model is equivalent to a 0.8% percent increase in LFBGP consumption. Reported as "CD_CEV" in output. Calculated in CDcompAnalysis.m, lines 269-283.
  - Environmental policy in the DTC model is equivalent to a 0.3% percent increase in LFBGP consumption. Reported as "DTC_cdcomp_CEV" in output. Calculated in CDcompAnalysis.m, lines 269-283.

- Section 5.1.2
  - Environmental policy in the DTC model is equivalent to a 0.3% percent decrease in LFBGP consumption. Reported as "DTC_lcp_CEV" in output. Calculated in Mainfile.m, lines 901-906.

References

Energy Information Administration (2019a): "Annual Energy Review," https://www.eia.gov/totalenergy/data/annual/ (accessed 8/5/19).

Energy Information Administration (2019b): "State Energy Data System," https://www.eia.gov/state/seds/seds-data-complete.php (accessed 8/5/19).

International Energy Agency (2018): "IEA Headline Energy Data," https://www.iea.org/data-and-statistics/data-product/world-energy-balances-highlights (accessed 8/5/19).

McGlade, C., and P. Ekins (2015a): "Data for: The geographical distribution of fossil fuels unused when limiting global warming to 2◦C," Nature, 517, 187, https://doi.org/10.1038/nature14016.

McGlade, C., and P. Ekins (2015b): "The geographical distribution of fossil fuels unused when limiting global warming to 2◦C," Nature, 517, 187.

Organization for Economic Cooperation and Development (2019): "Gross domestic spending on RD (indicator)," doi: 10.1787/d8b068b4-en (accessed 8/6/19).

Performance Curve Database (2019): "Photovoltaics 2," https://pcdb.santafe.edu/index.php (accessed 8/7/19).