Helios Solar Storm Scenario

3 November 2016

The Helios Scenario & Critical National Infrastructure and Macroeconomic Impacts

Centre for **Risk Studies**

UNIVERSITY OF CAMBRIDGE Judge Business School

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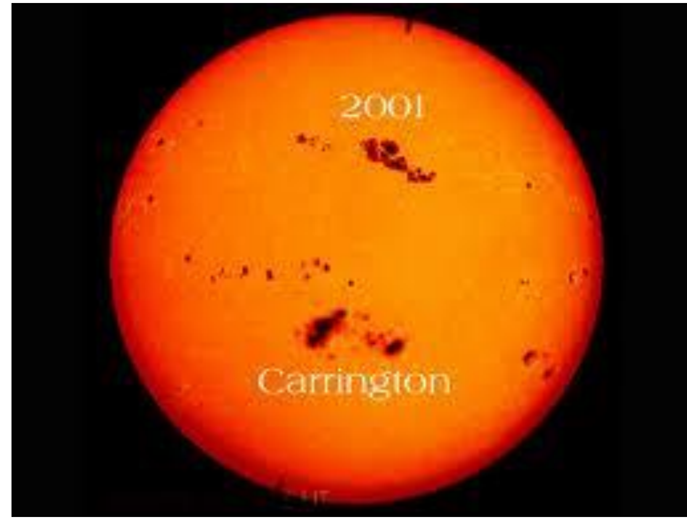
Cambridge Centre for Risk Studies

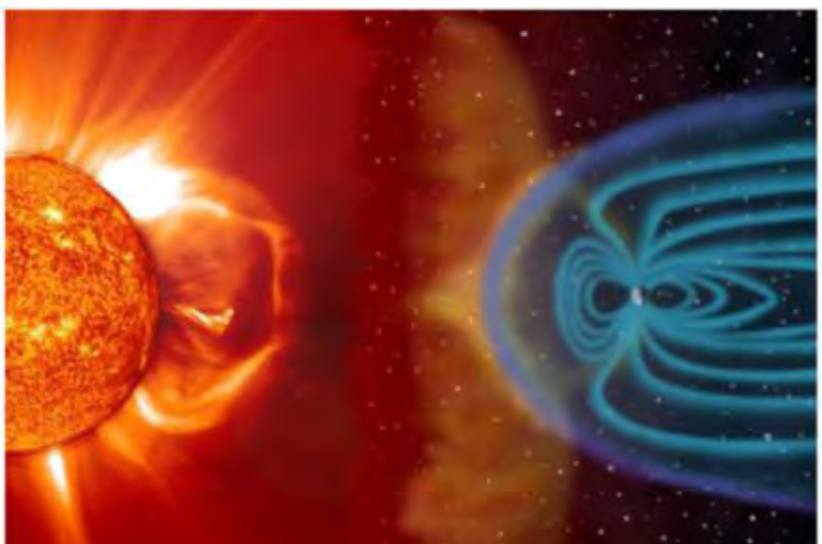
AIG

Phase 1 – Heightened Sunspot Activity

- Large group of sunspots show heightened activity
- STEREO A detects and monitors
  - NOAA/Met scientists take a special interest
- Relatively moderate CME and solar flare emitted
  - CME speed = ~ 450 km/s ± 500 km/s
  - Flare size (M5) = < $5x10^{-5}$ W/m^2
  - NOAA estimates a R2 Radio Blackout and a G2 category geomagnetic storm in four days' time



X1: 29 Mar 2001 and X28+ 29 Aug 1859
(Source: NASA)

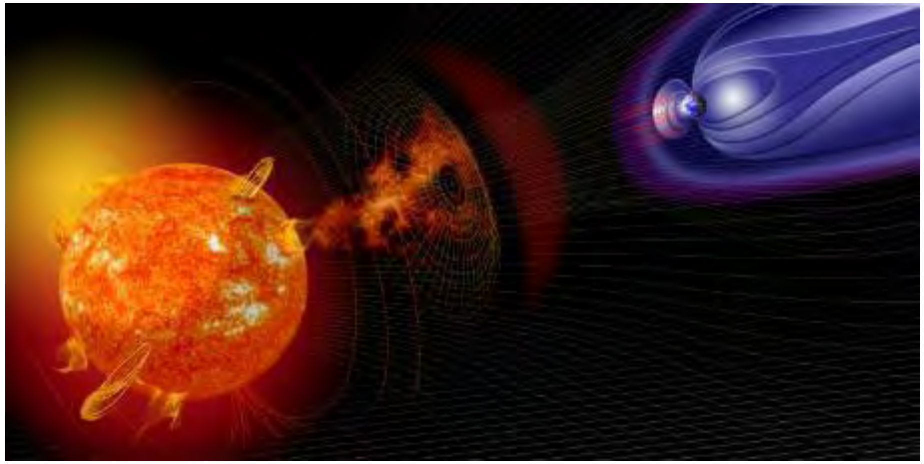


Kp Scale	NOAA G-Scale	National Grid Scale
Kp 9	G5	Category 5
		Category 4
		Category 3
		Category 2
Kp 8 to 9-	G4	Category 1
Kp 7	G3	
Kp 6	G2	
Kp 5	G1	
Kp < 5		

CME = coronal mass ejection

Scal Source: Richards, Andrew. "Impacts of Extreme Space Weather on GB Electricity Network." 18 September 2015.

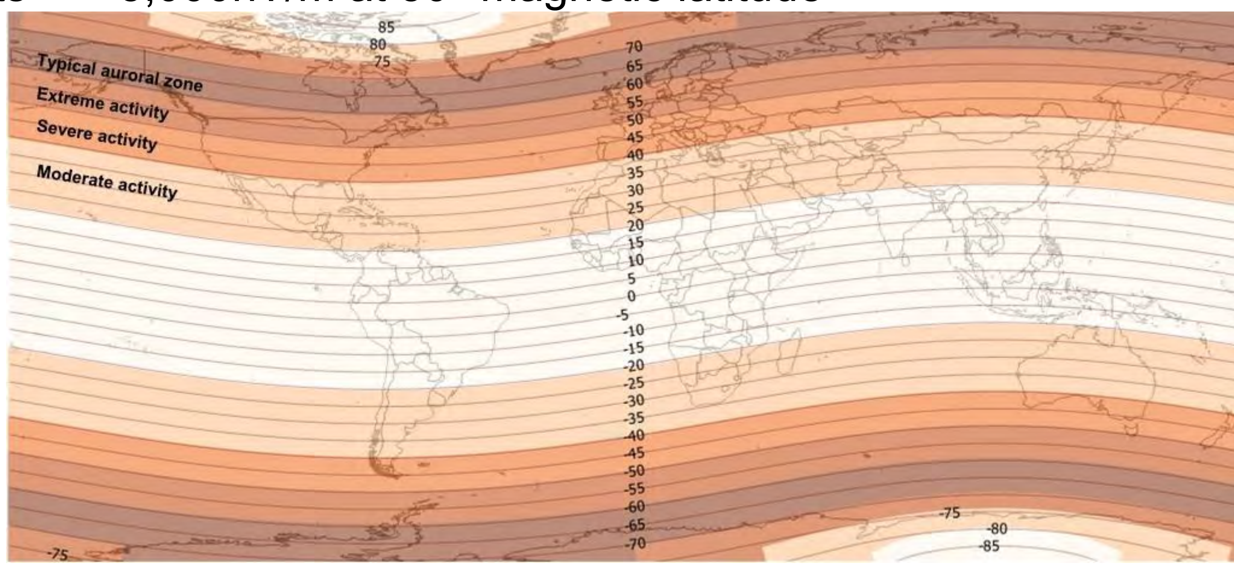
Phase 1 - Activity at the Sun



- Sunspot group continues to be highly active
- Three days later, a large build up of energy due to an efficient magnetic reconnection process, leads to a giant high-mass CME being discharged towards Earth
  - CME speed = ~2,000km/s ± 500km/s
  - Flare size (X20) = $2x10^{-3}$ W/m^2
  - Solar radiation storm = 10^4 MeV
- The interaction effect between the moderately-sized CME a number of days earlier, preconditions the interplanetary space
  - This lowers the ambient solar wind density, producing very little deceleration

Phase 2 – CME Arrives at Earth

- Satellite systems provide 30-60 minutes warning of incoming CME
  - The CME bombards Earth's magnetosphere, forcing a reconfiguration between the southward-directed interplanetary magnetic field and Earth's geomagnetic field
- The second CME reaches Earth in only 20 hours
  - Consequently billions of tonnes of gas containing charged particles intensify the shock compression
  - Particles are accelerated along the magnetotail, back towards Earth being deposited in the auroral ionosphere and magnetosphere on the night side of the Earth, directly above North America
  - Dst measurements = ~ -1000nT
  - dB/dt measurements = ~ 5,000nT/m at 50° magnetic latitude



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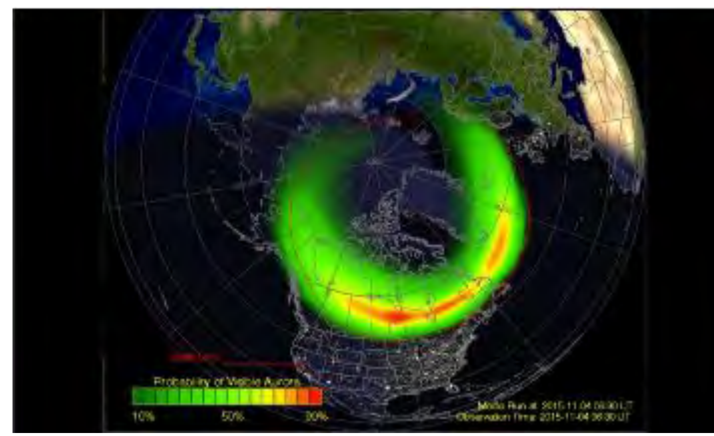
Notes: The contour lines on this map were generated using the World Magnetic Model (WMM) 2015 shape file from NOAA (Chulliat, 2014).

Phase 2 – Geomagnetic Storm on Earth

- Auroral oval forced equatorward by 15° magnetic latitude
- Numerous substorms take place every few hours on the dawn-to-dusk side of the Earth due to the highly dynamic nature of the auroral electrojet roughly 100km above ground
- Geomagentic effects
  - Rapid change in the magnetic field rate-of-change down to 50° magnetic latitude
  - Ring current intensifications take place down to 20° magnetic latitude

(Source: Svein-Magne Tunli, https://commons.Wikimedia.org)

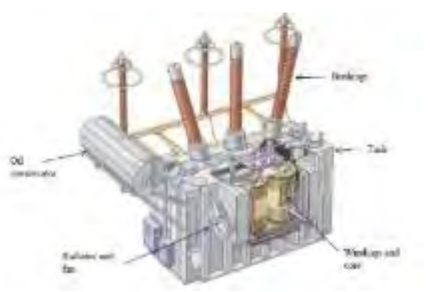


(Source: Space Weather Prediction Centre, National Oceanic and Atmospheric Administration, www.swpc.noaa.gov/)

Phase 3 – EHV Transformers Damaged

- Due to intense electrojet and ring current activity key electricity network assets are placed under significant strain
- Extra High Voltage (EHV) transformers are at risk
- Due to lack of adequate warning utility operators do not have time to fully implement emergency procedures
  - Some EHV transformers automatically trip off and others have to be manually shut off
  - Grid instability ensues causing a complete voltage collapse
  - In some cases, degradation to windings and insulation cause failure within 48 hours
- Total US EHV transformers damage distribution

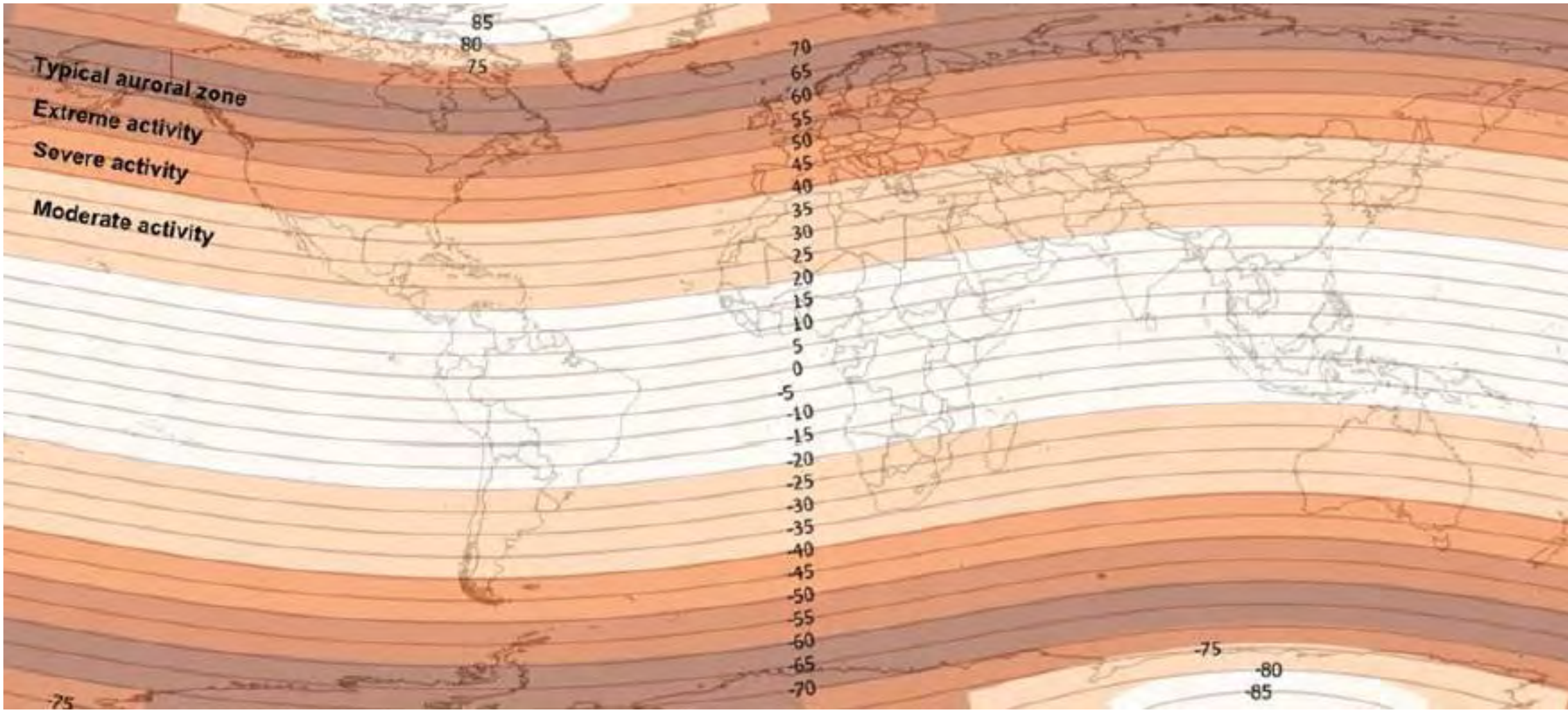
EHV Transformer



S1	D0 Not affected	D1 Tripped off	D2 Minor damage	D3 Major damage	D4 Destroyed
No. of transformers with spare	159	53	6	0	0
No. of transformers without spare	1,432	559	115	11	0
Total no. of transformers damaged	1,595	612	121	11	0
S2 and X1	**D0**	**D1**	**D2**	**D3**	**D4**
No. of transformers with spare	118	67	22	3	0
No. of transformers without spare	1,006	703	313	74	5
Total no. of transformers damaged	1,152	770	335	77	5

Image Source:
DOE. Large Power Transformers and the US Electric Grid. April 2014 Update. Page 5.

Geomagnetic Latitude Threat Map



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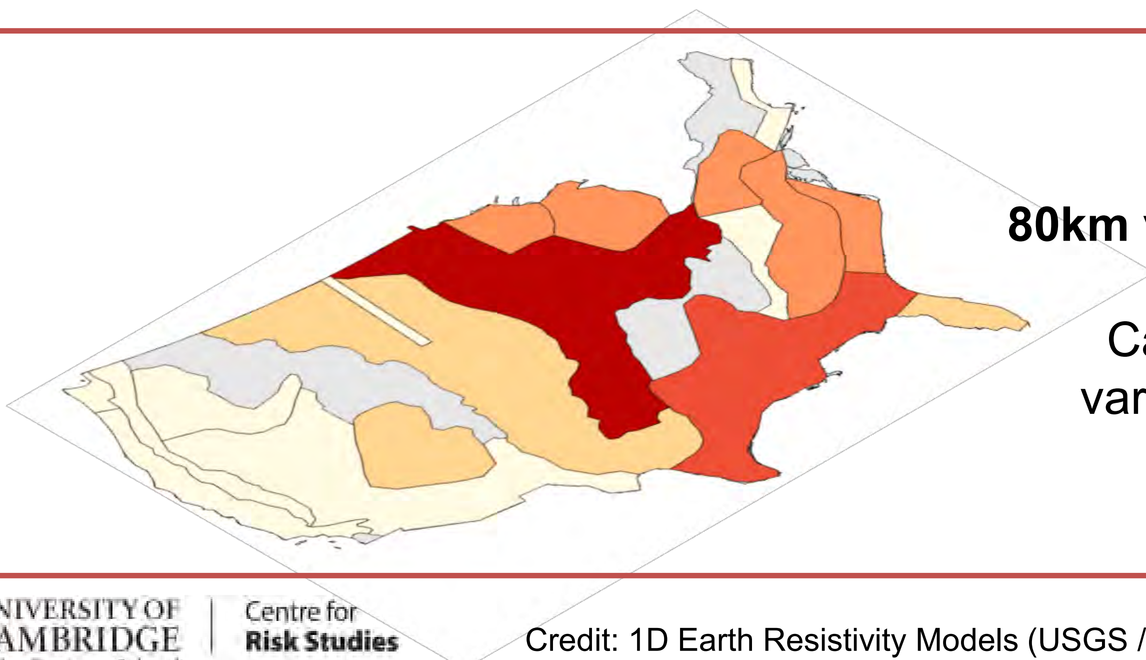
Ground Conductivity by State



80km vertical weighted average

Captures high amplitude variations in the production of GIC

Credit: 1D Earth Resistivity Models (USGS / Fernberg, 2012)

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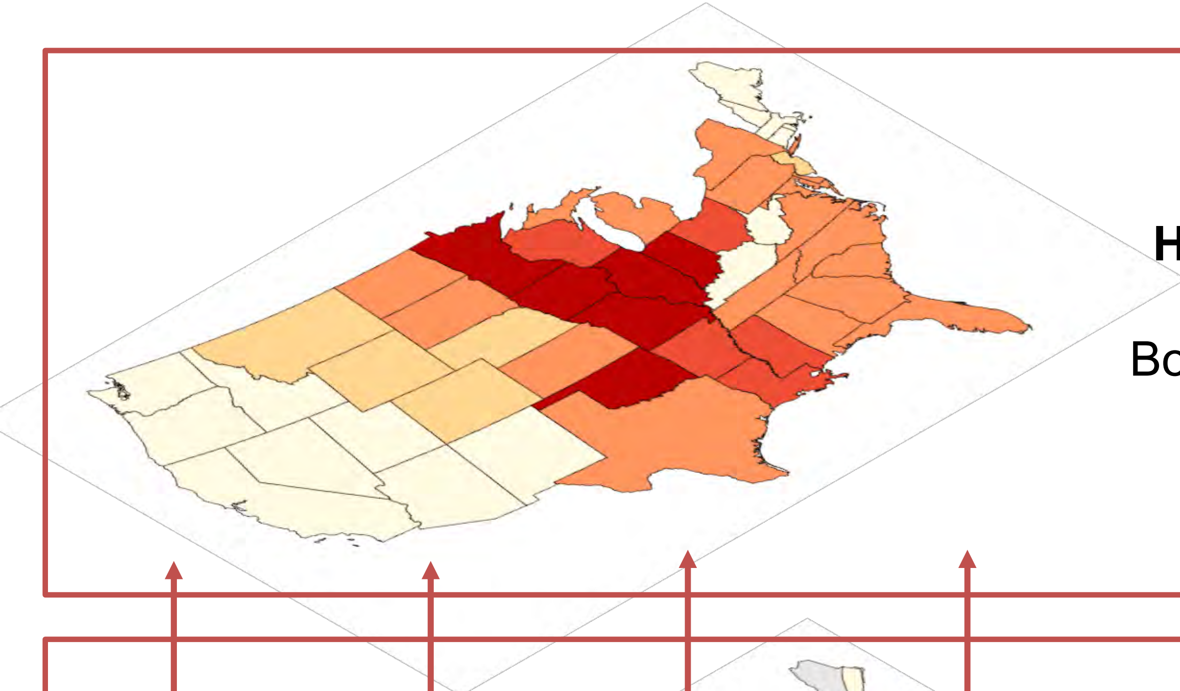
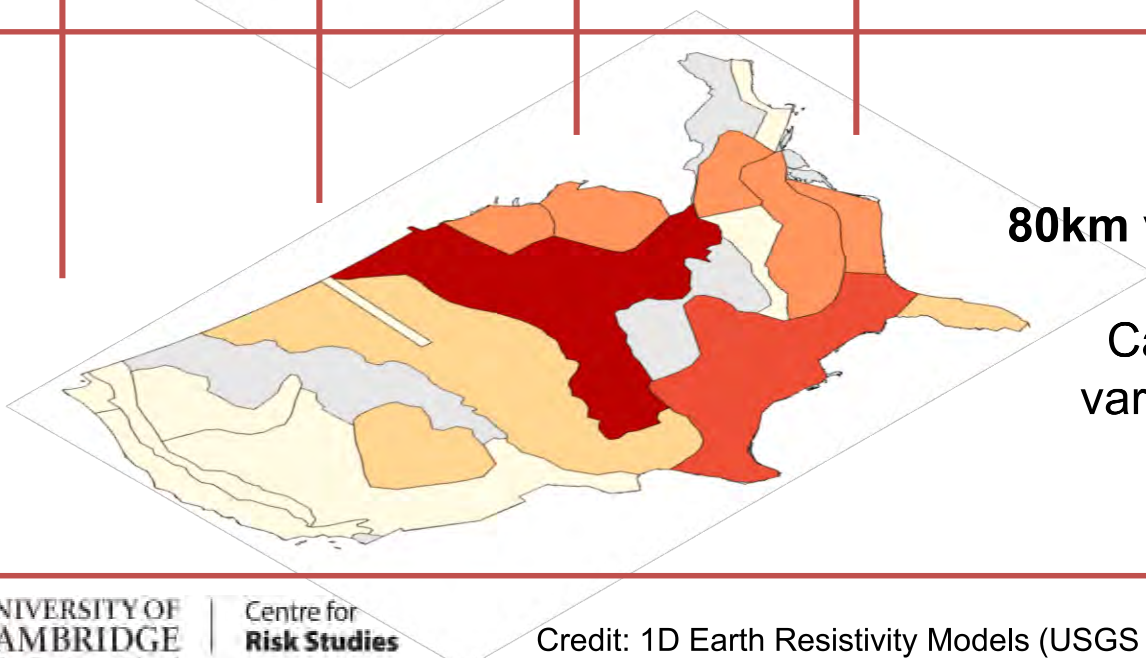


Horizontal weighted average

Boundaries of geological regions intersected with US State boundaries



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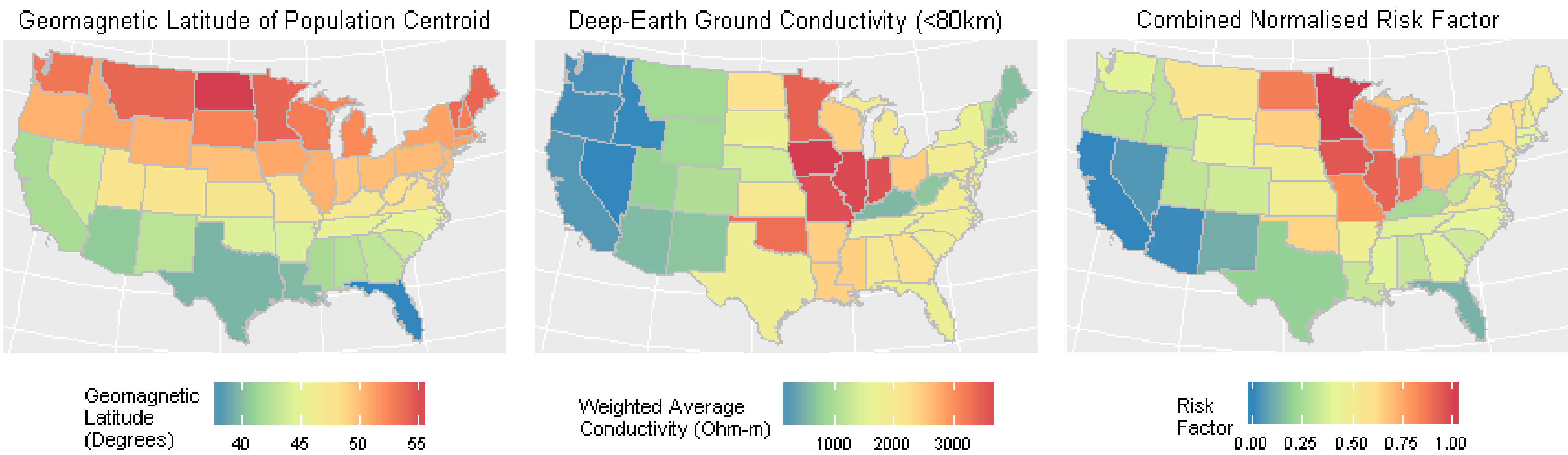
State Level Risk Matrix



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EHV Transformers by State

FERC Federal Energy Regulatory Commission

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Form 1 - Electric Utility Annual Report

Viewer - Instructions and Download

Note: This also applies to **Form 1–F and Form–3Q** - Comprehensive Quarterly Financial and Operating Report

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You will save yourself a lot of time by referring to this page **first**, before contacting FERC with problem issues. Most problems will involve Internet communication issues which are addressed below. Of course, we make mistakes - and need to fix things on the server or with the software, so we do not mind emails, questions, and suggestions.

Downloading and Viewing the Form 1 Database

The public version of the Form 1 database is available for partial or complete download to client sites and may be viewed with the Form 1 Database Viewer. The Database Viewer will permit the selection, viewing and printing of individual or all Form 1 or 1-F annual submissions for 1994 through the last filing year and quarterly (3Q) filings submitted in the past.

The resulting Form 1 Database downloaded to the local client may be manipulated for specific reporting or analysis needs using Microsoft Visual FoxPro (VFP) or commercially available reporting software such as Crystal Reports or others that support the VFP database container structure. Learn how to connect to a Visual FoxPro Database through Microsoft Access to access the Form 1 database.

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Data
- Data (Current and Historical)
- Connecting to a Visual FoxPro Database Through Microsoft Access

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Viewer
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- Instructions & Download

Database Utility
- Software EXE

QUICK LINKS
- Electric Industry
- FAQs: Forms

Transformer Damage Distribution

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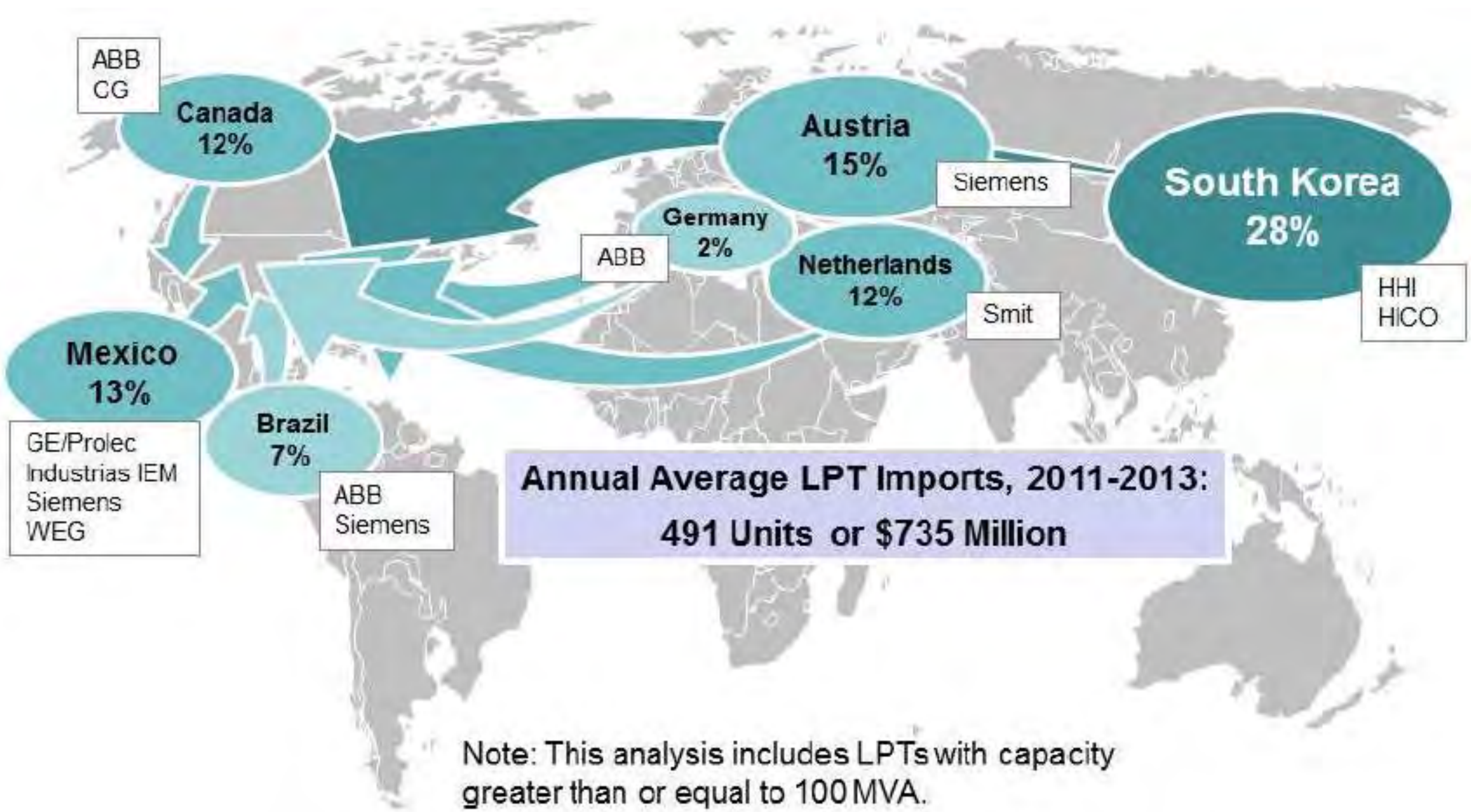
Phase 3 – Extended Power Restoration

- Tripped off transformers can be brought back on-line quickly
- Minor and major damaged transformers are transported to a workshop for repair
- If a spare is available it can be brought in from a storage facility within 14 days
- Manufacturing Concerns
  - Custom built and designed
  - Average lead time is 5 to 21 months
- Transportation Concerns
  - Rail transport requires special Schnabel railcars due to weight
  - Road transport requires Goldhofer vehicle and road permits/plans
- Restoration Times (days) for damaged EHV transformers

S1 and S2	D0 Not affected	D1 Tripped off	D2 Minor damage	D3 Major damage	D4 Destroyed
Outage for transformers with spare (days)	0	3	14	14	14
Outage for transformers without spare (days)	0	3	91	182	243
X1	D0	D1	D2	D3	D4
Outage for transformers with spare (days)	0	10	30	30	30
Outage for transformers without spare (days)	0	10	152	304	365

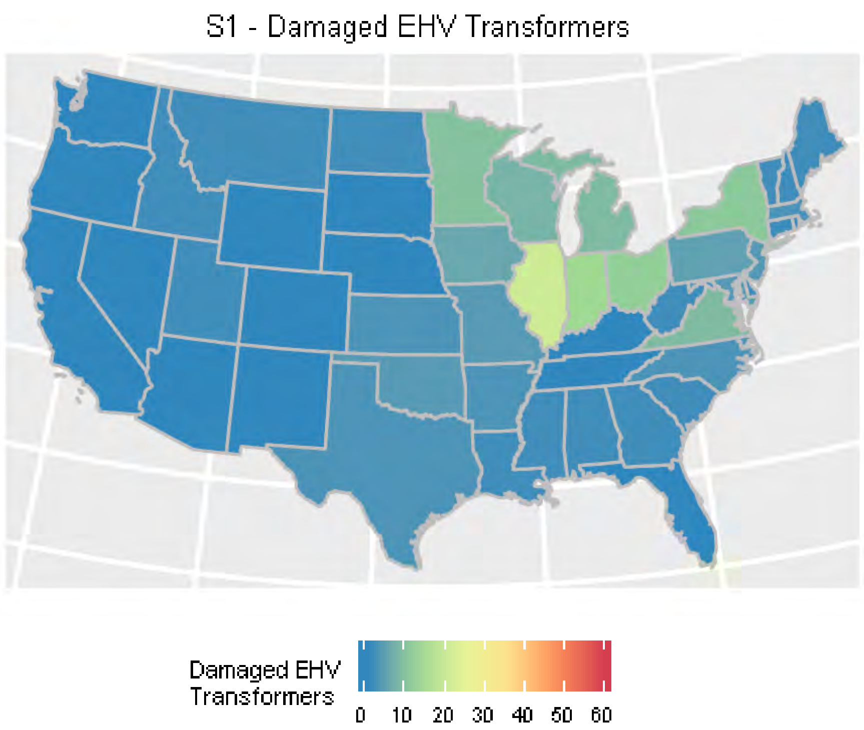
(Source: T&D World Magazine, tdworld.com)

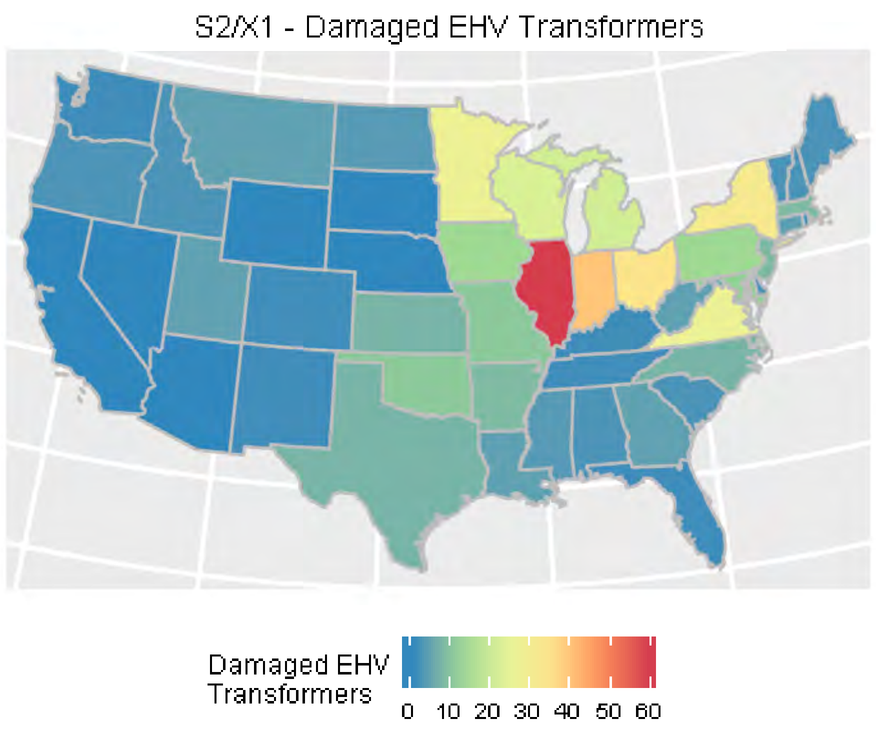
Transformer Manufacturing Supply Chain



(DOE, 2014)

Damaged Transformers by State





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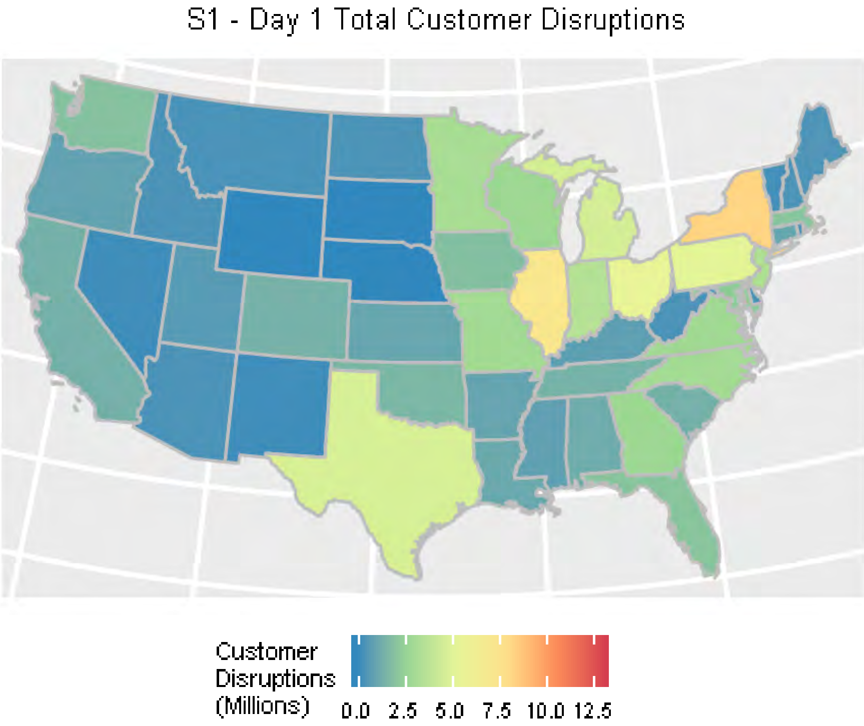
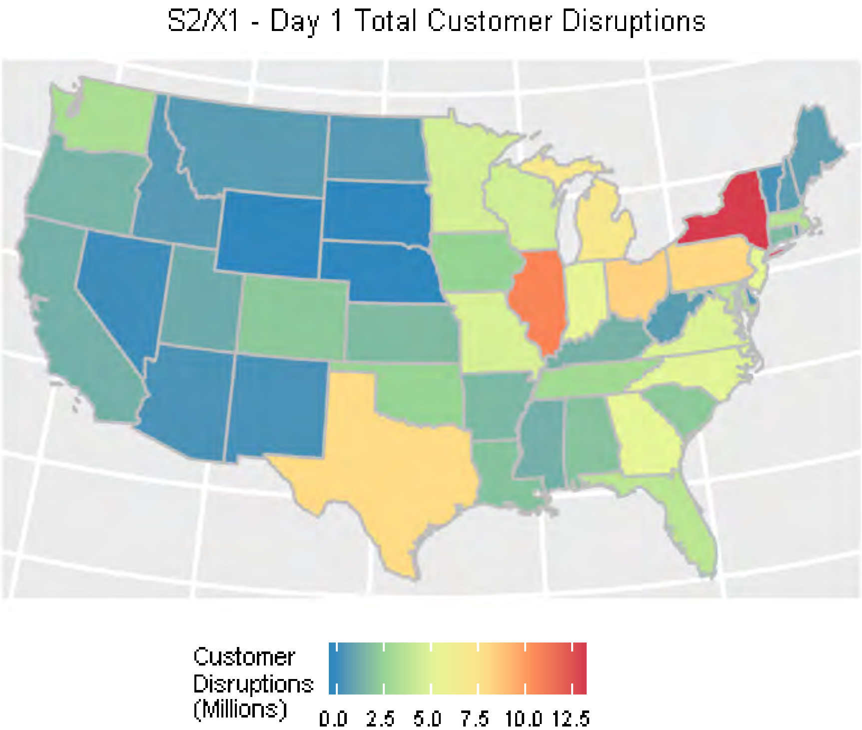
Customer Disruptions





Transformer Restoration Time

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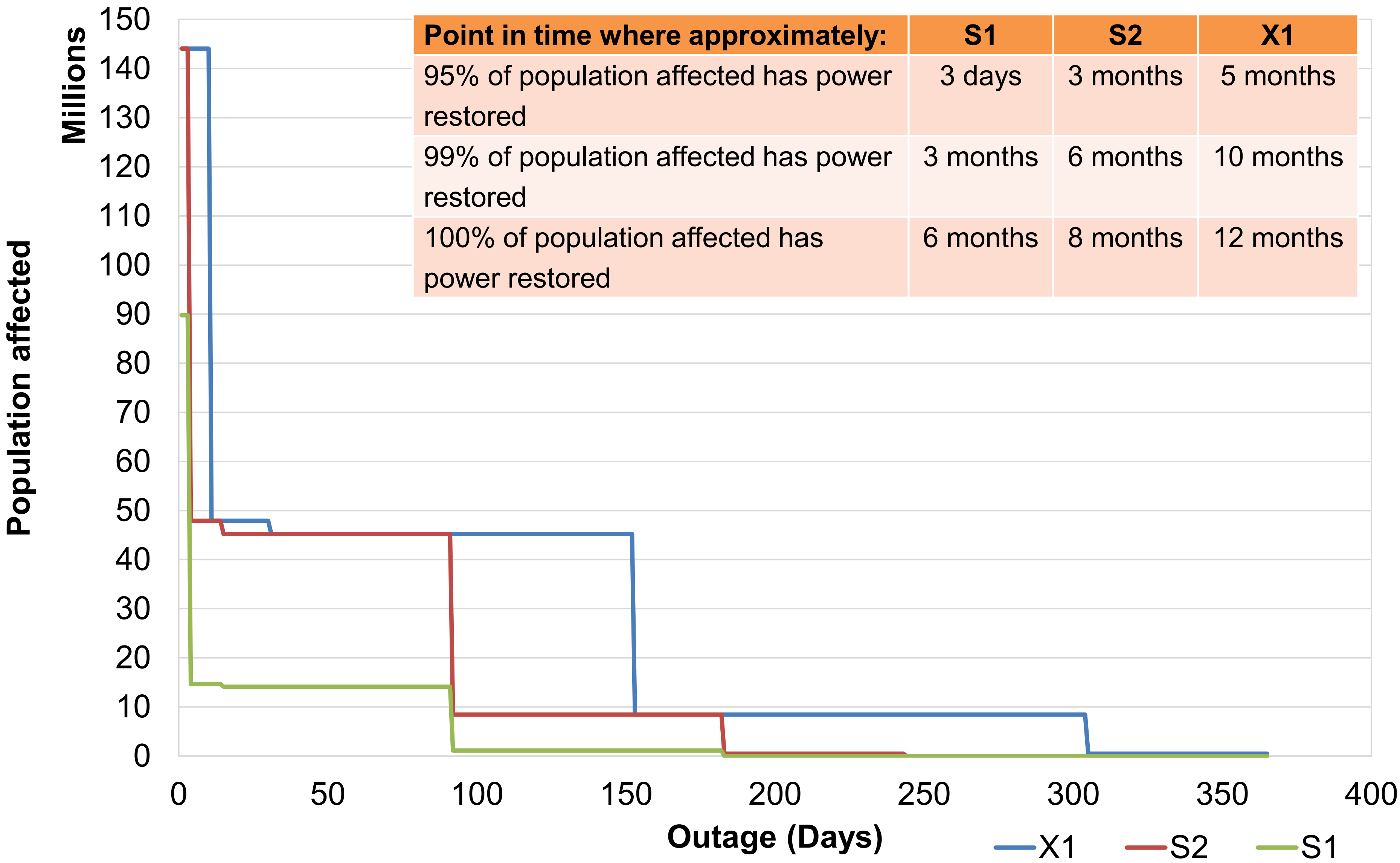
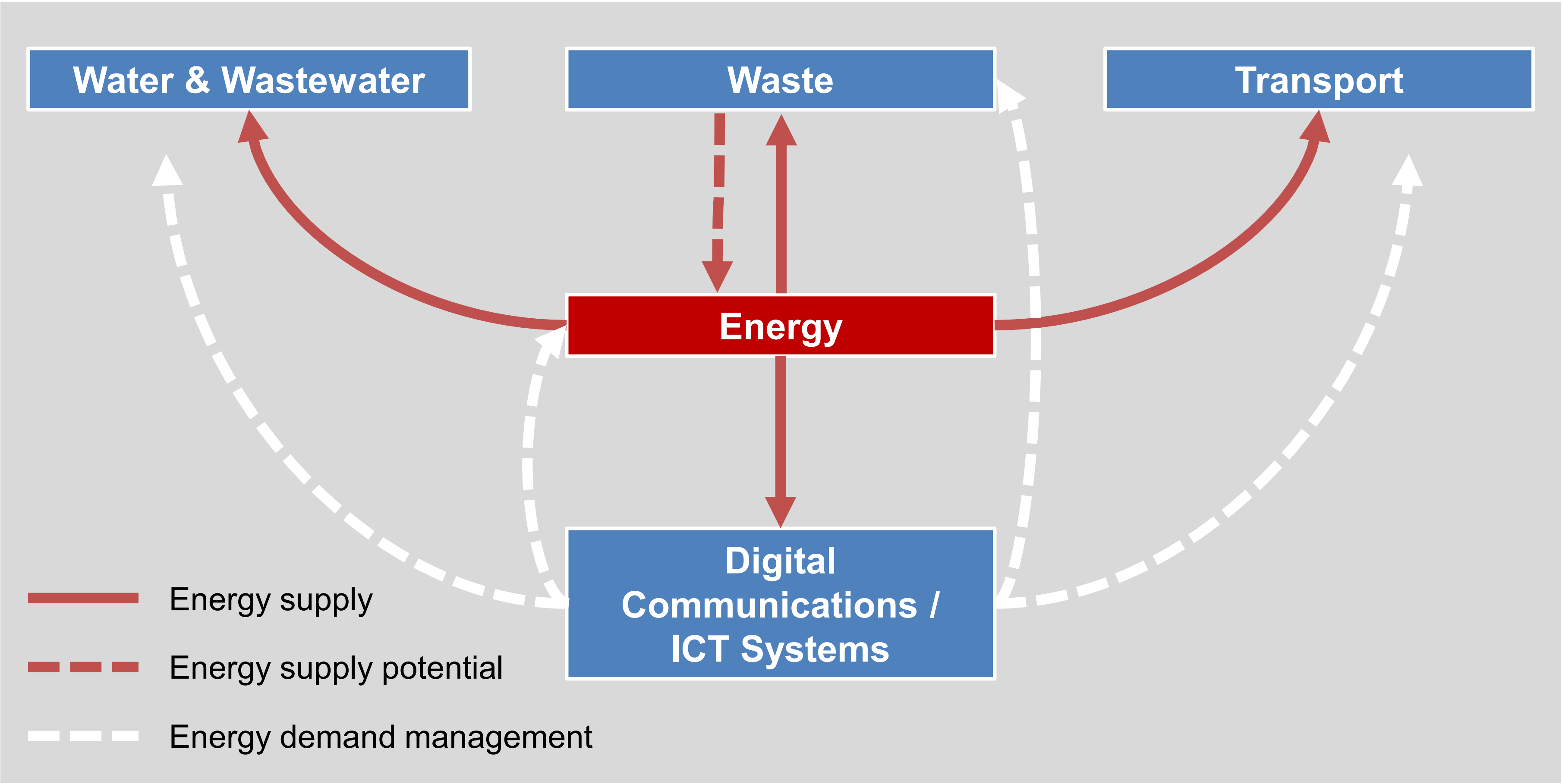
US Power Restoration Curves



Point in time where approximately:	S1	S2	X1
95% of population affected has power restored	3 days	3 months	5 months
99% of population affected has power restored	3 months	6 months	10 months
100% of population affected has power restored	6 months	8 months	12 months

Phase 4 - Aftermath



- Electromagnetic bursts from the solar flare (NOAA R5 radio blackout) and severe (S4) radiation storm cause
  - Disturbances in the ionosphere disrupt GPS/GNSS

Frequency and Severity

- Estimates developed are not robust because of the short time-series (Hapgood, 2011)
- Riley (2012) assumes that the Carrington event has a 12% probability of occurring every 79 years
- Love et al. (2015) estimates that a storm larger than Carrington (-Dst = ≥ 850 nT) occurs about 1.13 times per century
  - Moreover, a 100-year geomagnetic storm is identified as having a size greater than Carrington (-Dst = ≥ 880 nT)
- RAE report states that solar storms are a random process and the potential does not increase as time passes
- We proposed a Carrington sized event that hits Earth with a CME similar to the 2012 near miss

Methodology

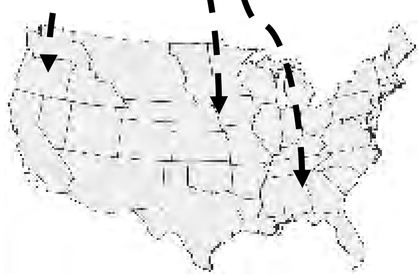
Scenario Variants

S1

S2

X1

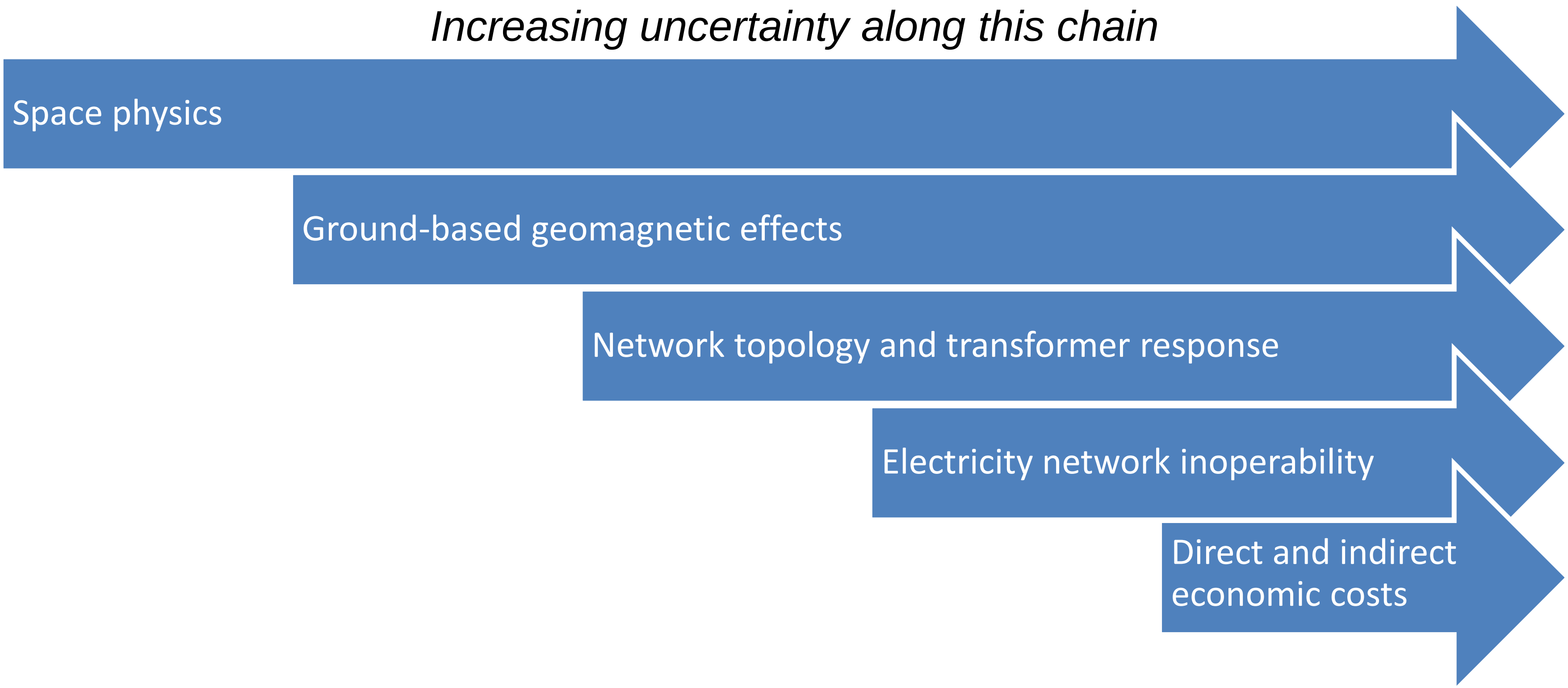
Method 1
State-level Multi-criteria Risk Matrix



Method 2
Calculation of Direct Costs to Economic Sectors

Method 3
Estimation of Indirect Costs to Domestic and International Supply Chains

The Challenge: The Economics of Solar Storms



What is Input-Output Modelling?

1973 Nobel Prize in Economics

Wassily Leontief (1906-1999)

(Source: Keystone/Hulton Archive, www.gettyimages.co.uk/)

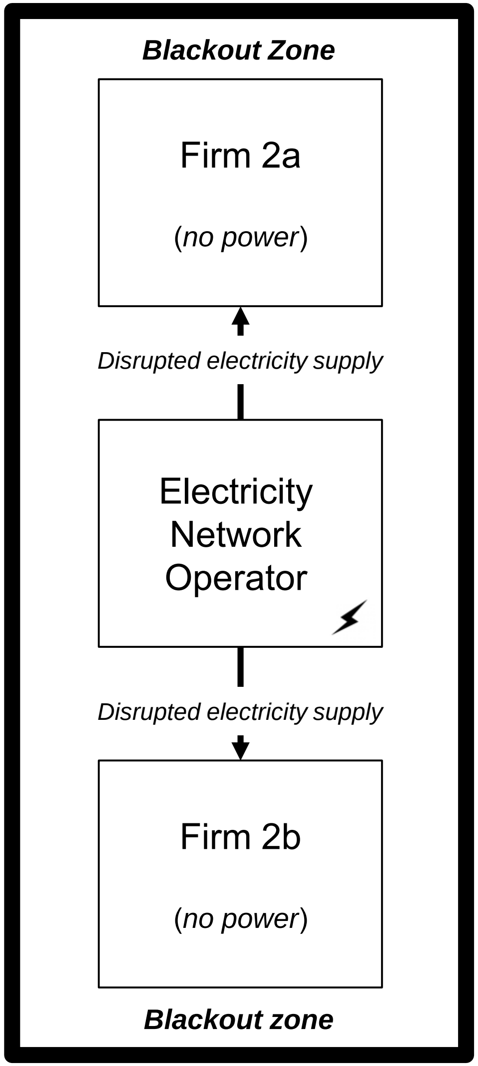
Important Assumption 1

All economic activity is dependent on electricity

Important Assumption 2

The number of customer disruptions by state is comparable to lost economic output

Direct and Indirect Economic Impacts



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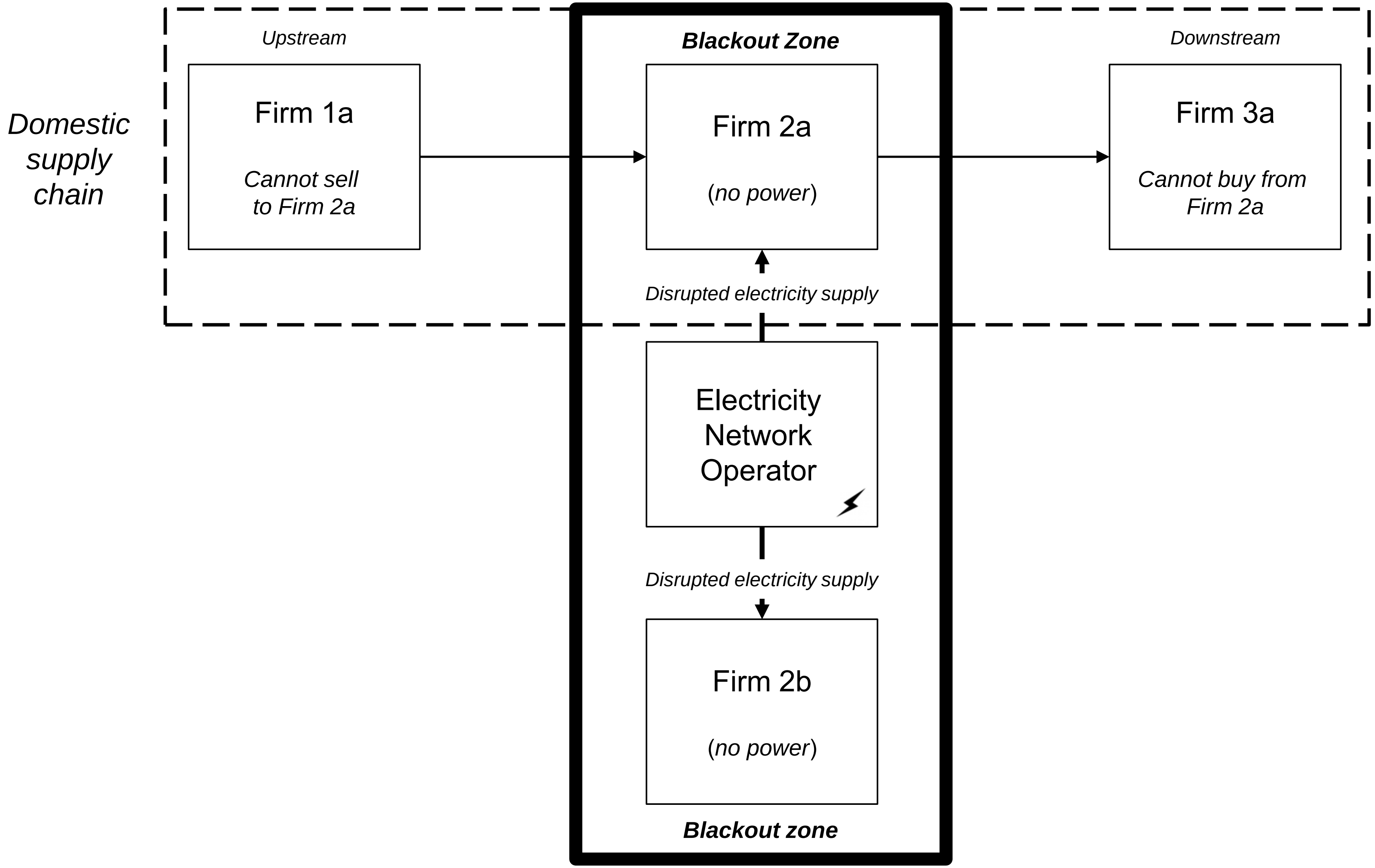

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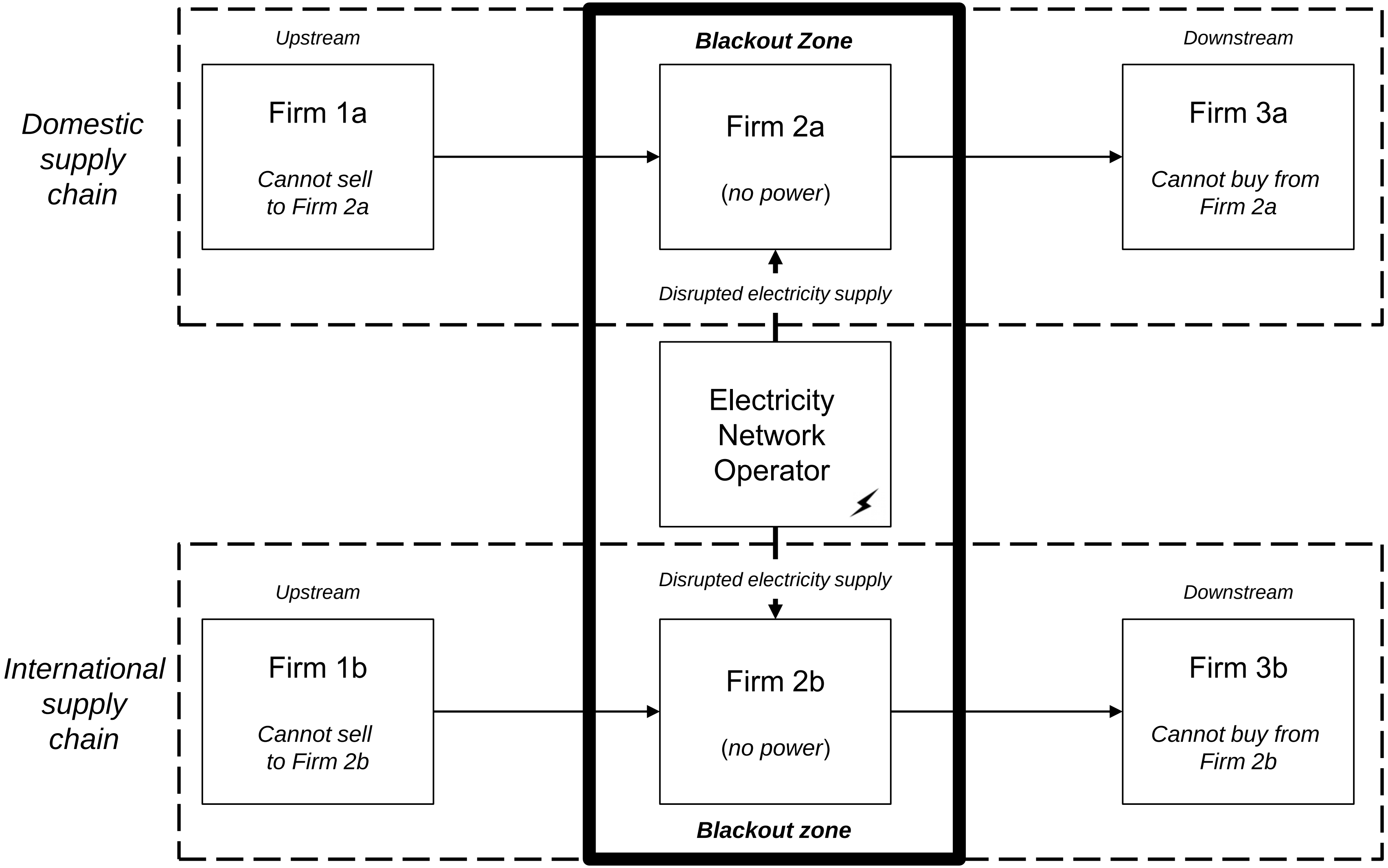

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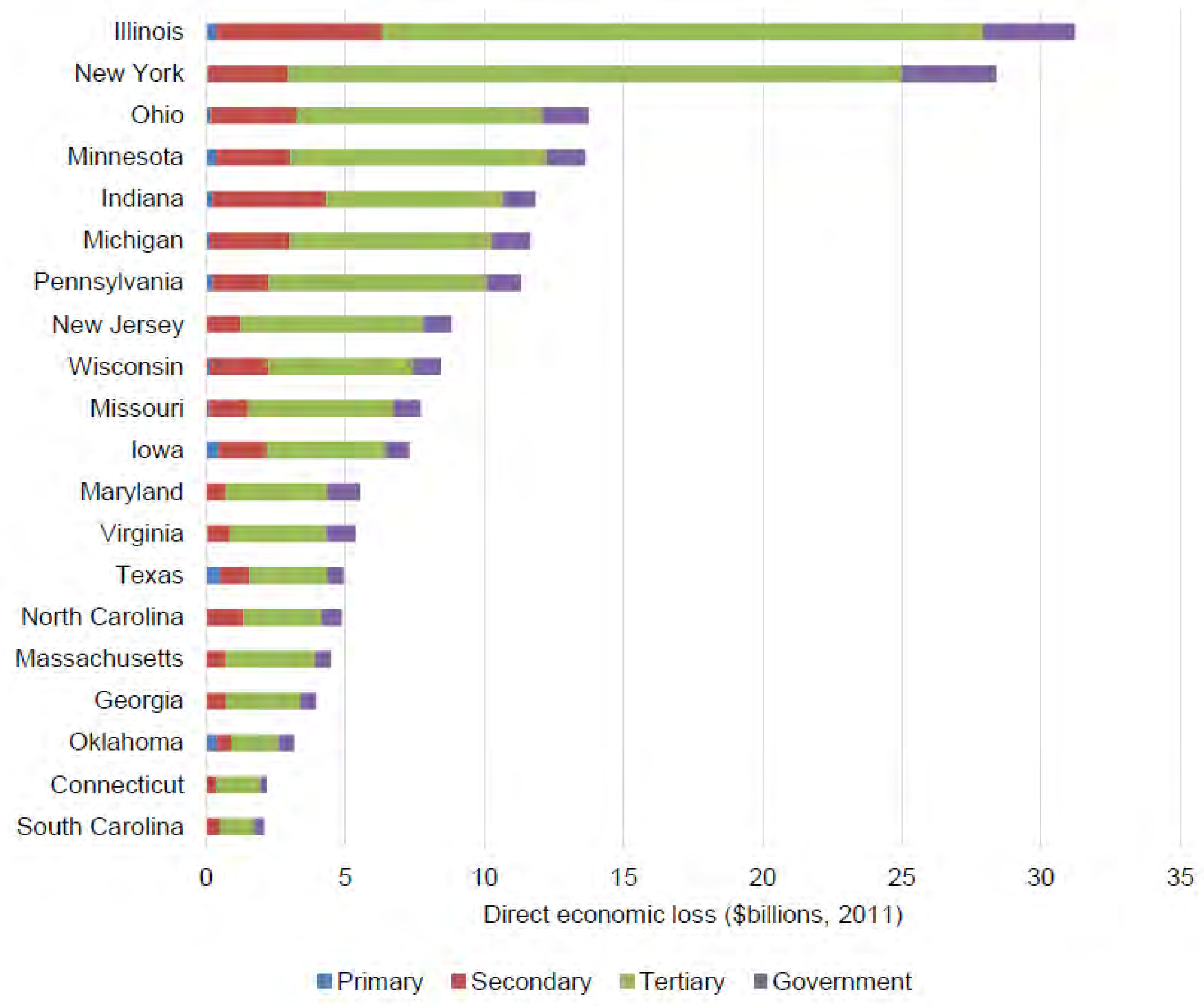
Direct Economic Impacts by Industrial Sector (S1)



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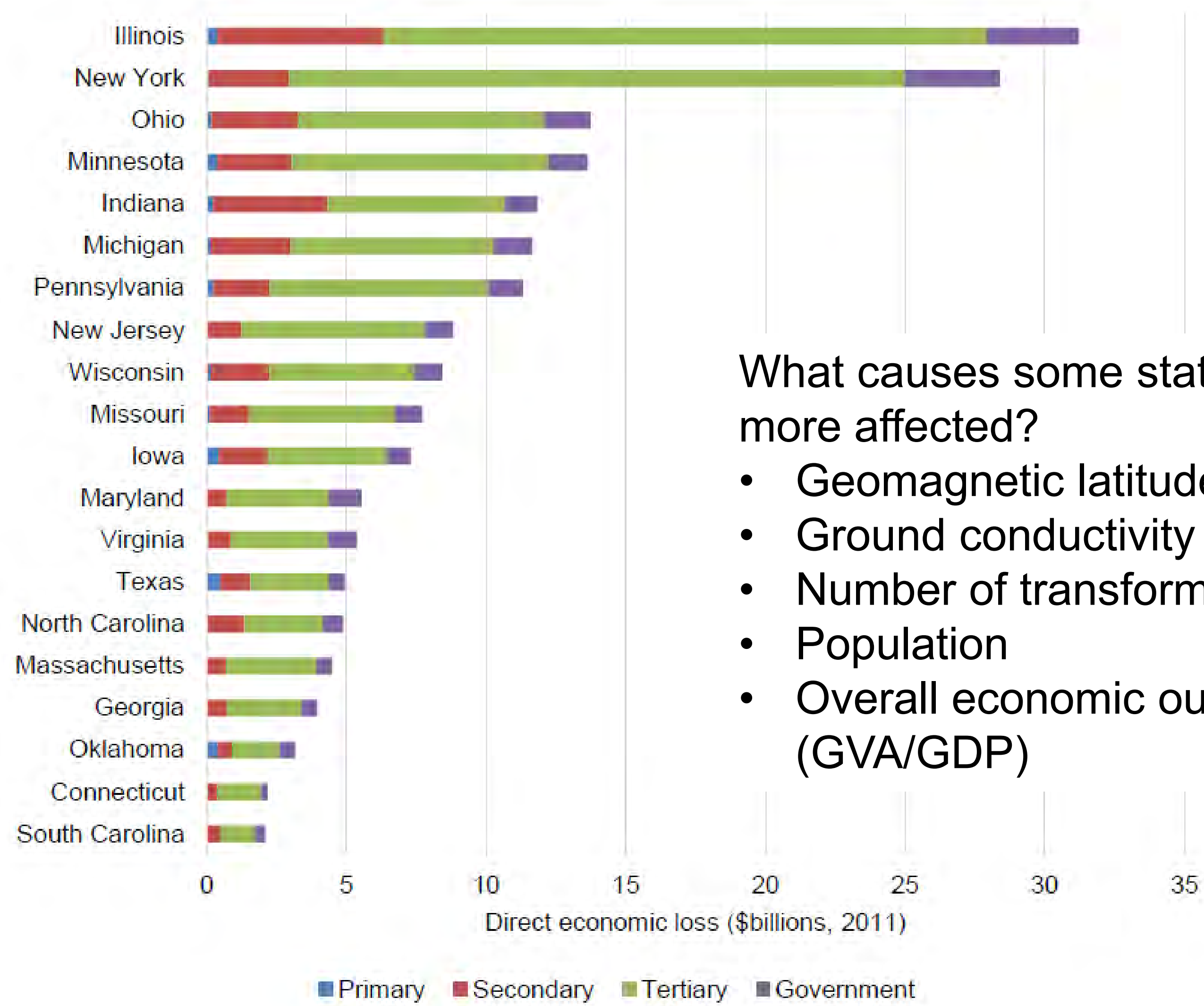
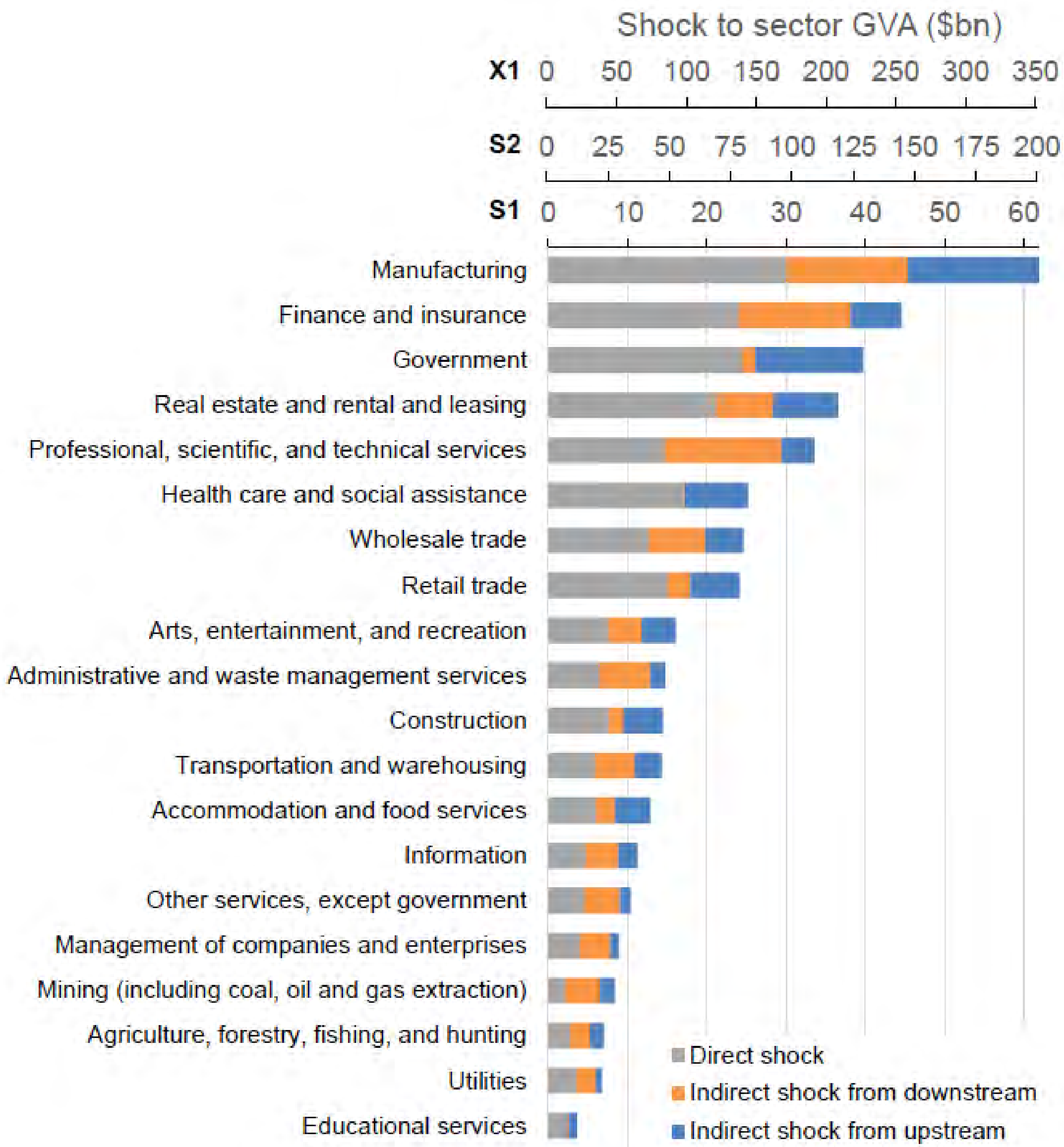


What causes some states to be more affected?

- Geomagnetic latitude
- Ground conductivity
- Number of transformers
- Population
- Overall economic output (GVA/GDP)

US Sectoral Supply Chain Impacts



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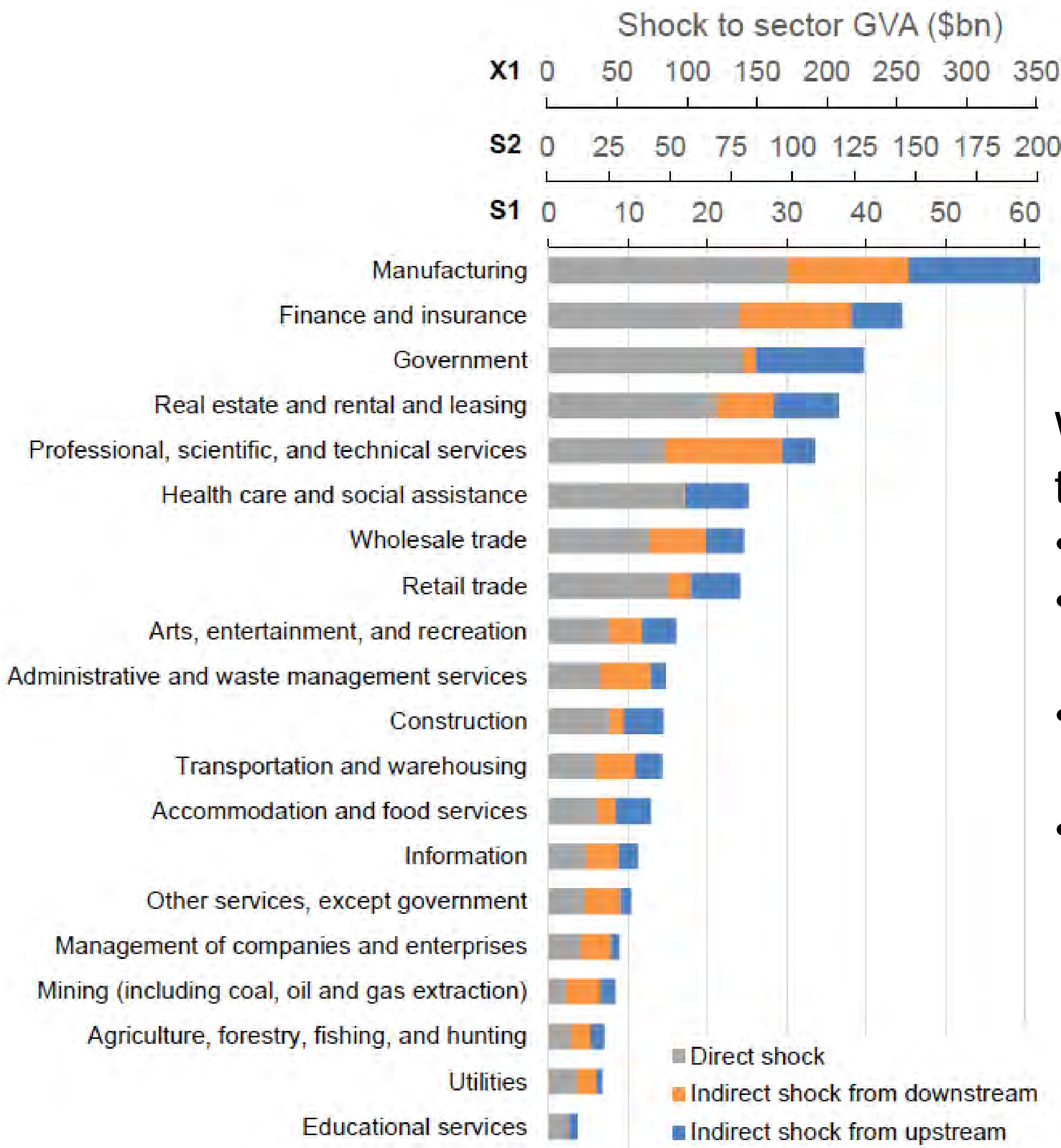
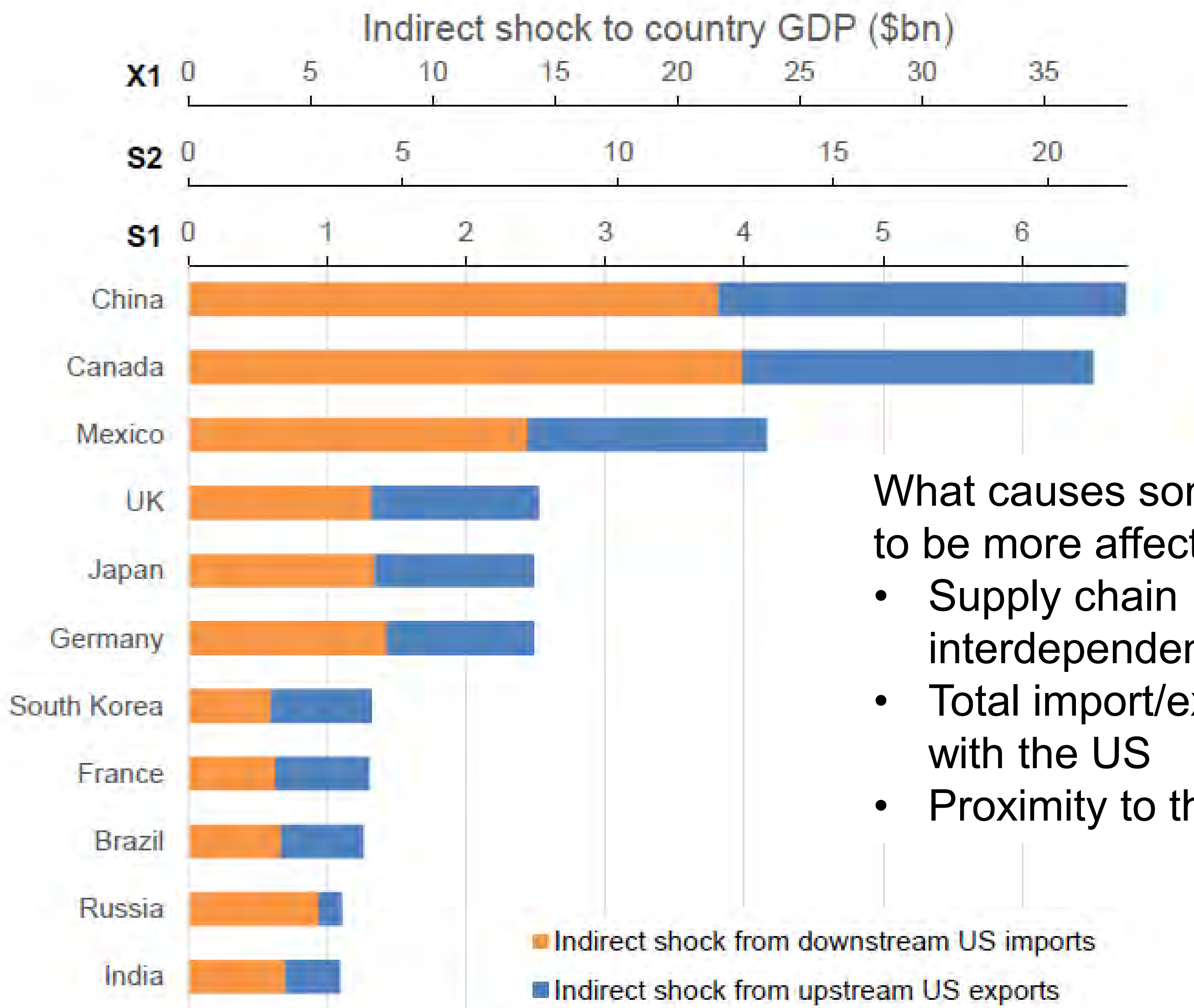


What causes some sectors to be more affected?

- Industrial clustering
- Overall economic output (GVA/GDP)
- Interdependence on other economic sectors
- Length of supply chains

International Supply Chain Impacts



What causes some countries to be more affected?

- Supply chain interdependencies
- Total import/export trade with the US
- Proximity to the US

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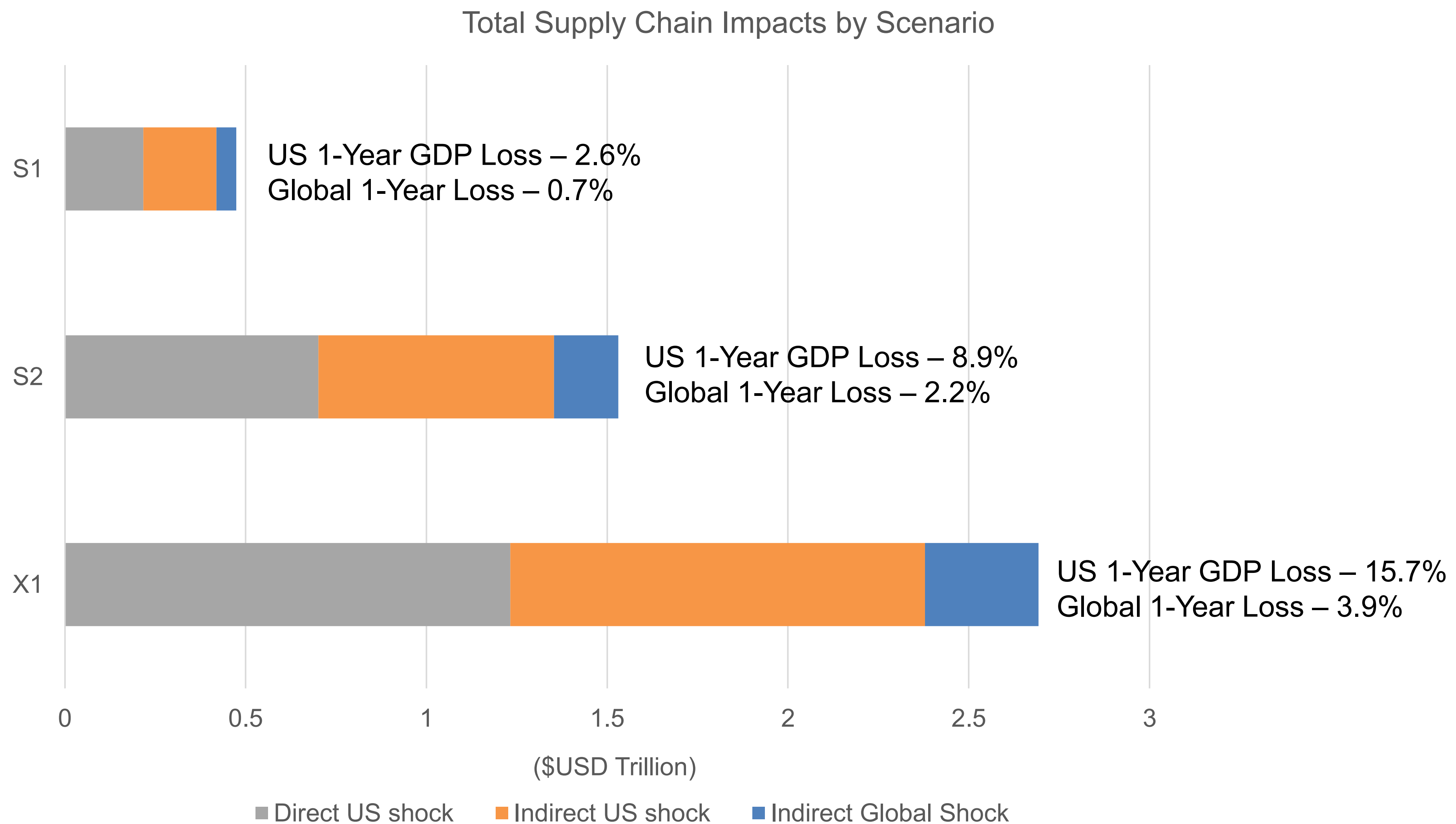
Scenario Results



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Economic Impacts: Conclusions

- Key risk factors:
  - Geomagnetic latitude
  - Ground conductivity

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Economic Impacts: Conclusions

- Key risk factors:
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  - Ground conductivity
- New York State and Illinois are most affected
- Regionally, the Midwestern states see considerable disruption
- Sectors most affected:
  - Manufacturing
  - Finance
- Direct impact: $0.2-1.2 trillion
- Indirect US supply chain impacts: $0.2-1.1 trillion
- Indirect global supply chain impacts: $0.1-0.3 trillion