UMASS University of Massachusetts Lowell

Advanced Communication Networks Laboratory

Electricity Cost and Emissions Reduction in Optical Networks

Arash Deylamsalehi, Dylan Davis, and **Vinod M. Vokkarane**

IEEE Online Conference on Green Communications– November 16, 2016

Introduction

❖Information and communication technology (ICT) uses about **1500 TWh** of electricity annually.

❖The ICT ecosystem now approaches **10% global electricity consumption.**

❖Reduced to personal terms,

watching an hour of video weekly **> two new refrigerators (Annually)**

Introduction

❖ The growth in ICT energy demand will continue to be moderated by efficiency gains.

❖ The rate of improvement in the efficiency of ICT technologies started around 2005.

❖ Followed almost immediately by a **new era of rapid growth data traffic**, the emergence of wireless broadband for smartphone and tablets.

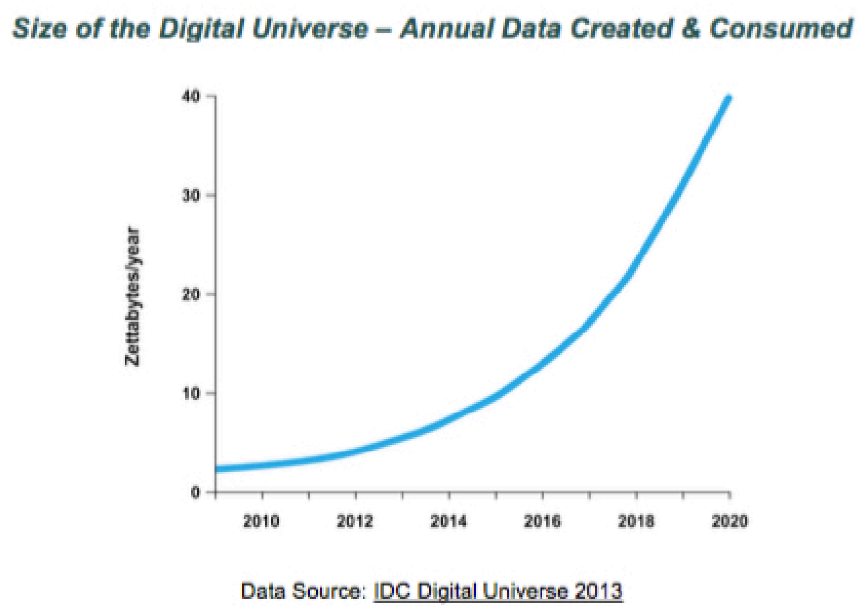
❖ Future growth in electricity to power the global ICT ecosystem is anchored in just two variables,

- Demand: how fast traffic grows
- Supply: how fast technology efficiency improves.

Introduction

❖ Hourly Internet traffic will soon exceed the annual traffic of the **year 2000.**

❖ Demand for bits has growth faster than the energy efficiency of using them.



"The digital universe is made up of images and videos on mobile phones uploaded to YouTube, digital movies populating the pixels of our high-definition TVs, banking data swiped in an ATM, security footage at airports and major events such as the Olympic Games, subatomic collisions recorded by the Large Hadron Collider at CERN, transponders recording highway tolls…"

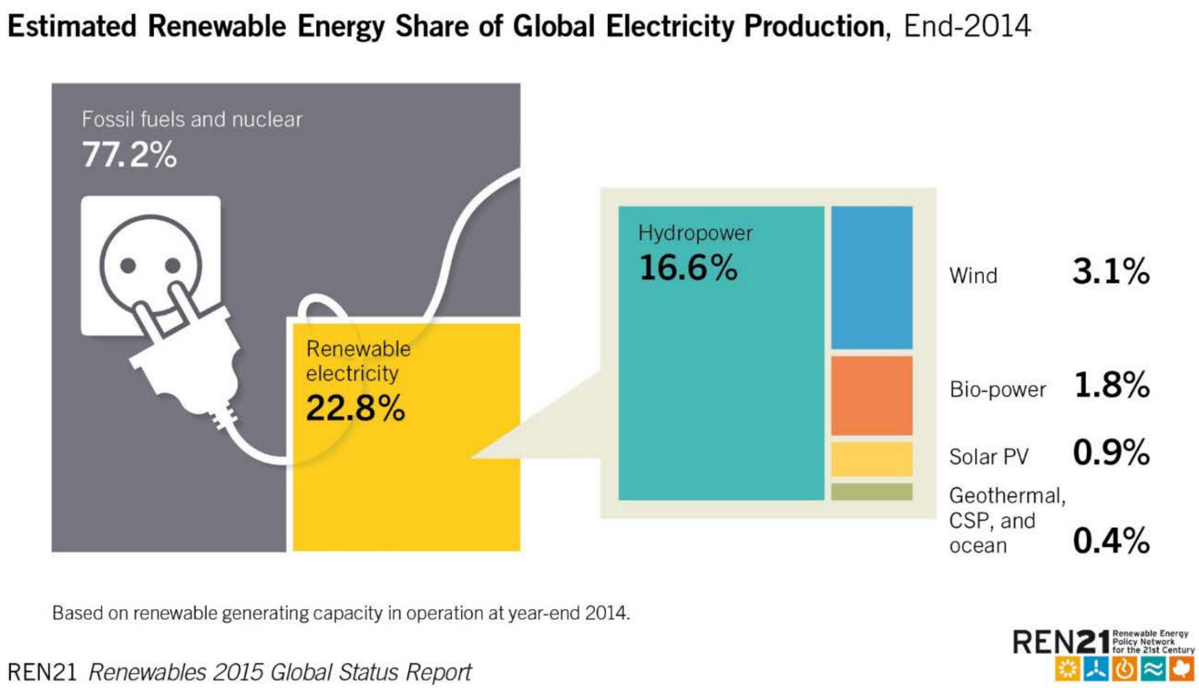
What is the Main Driver?

❖ **Main Driver of Energy Management in the ICT:**

- **Economic:** reducing the energy cost of ICT
- **Environmental:** reducing the carbon footprint
- **Technical:** reducing the associated heat dissipation

Introduction

❖ New power systems addressed them by :
- ➢ Renewable resources
- ➢ Deregulation of the energy market
- ➢ Smart Grid.



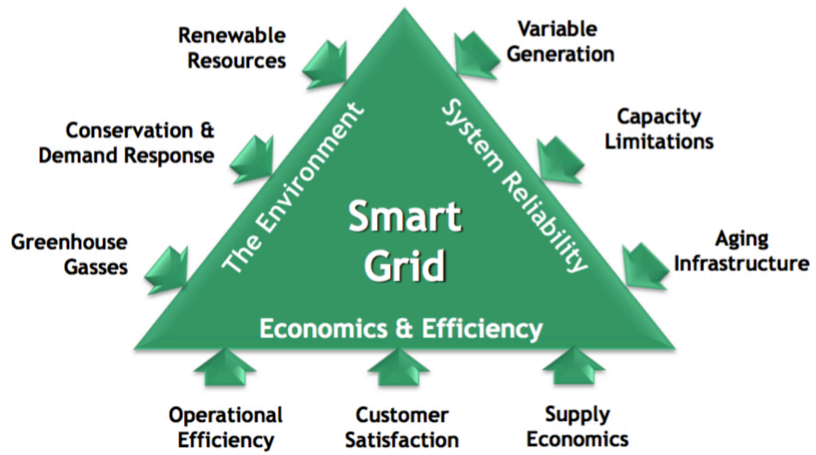
Smart grid

❖ The U.S Department of Energy **(DOE):**

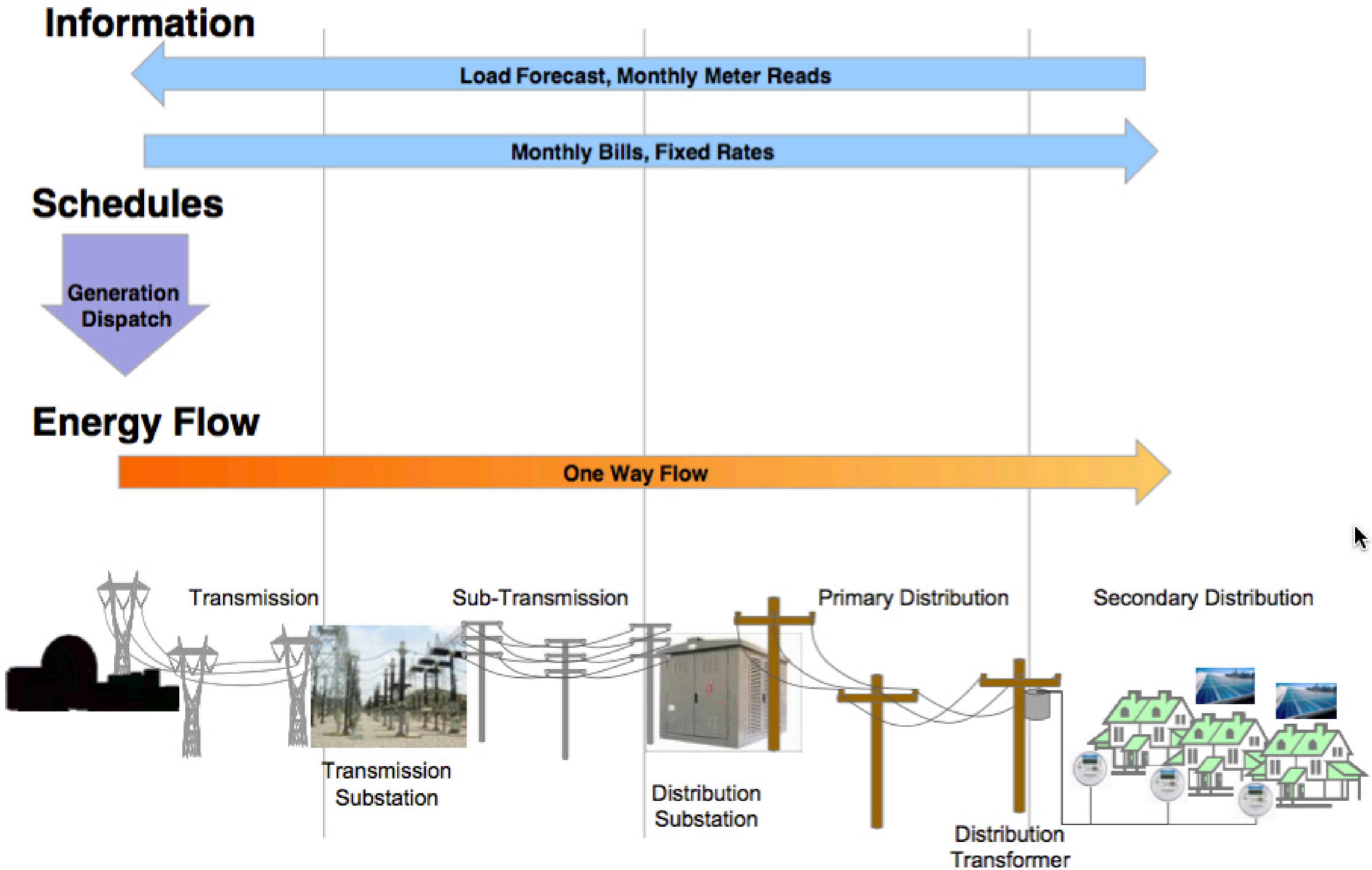
An automated widely distributed energy delivery network characterized by **a two-way flow of electricity and information, capable of monitoring and responding to changes in everything** from power plants to customer preferences to individual appliances.

❖ National Institute of Standard and Technology **(NIST):**

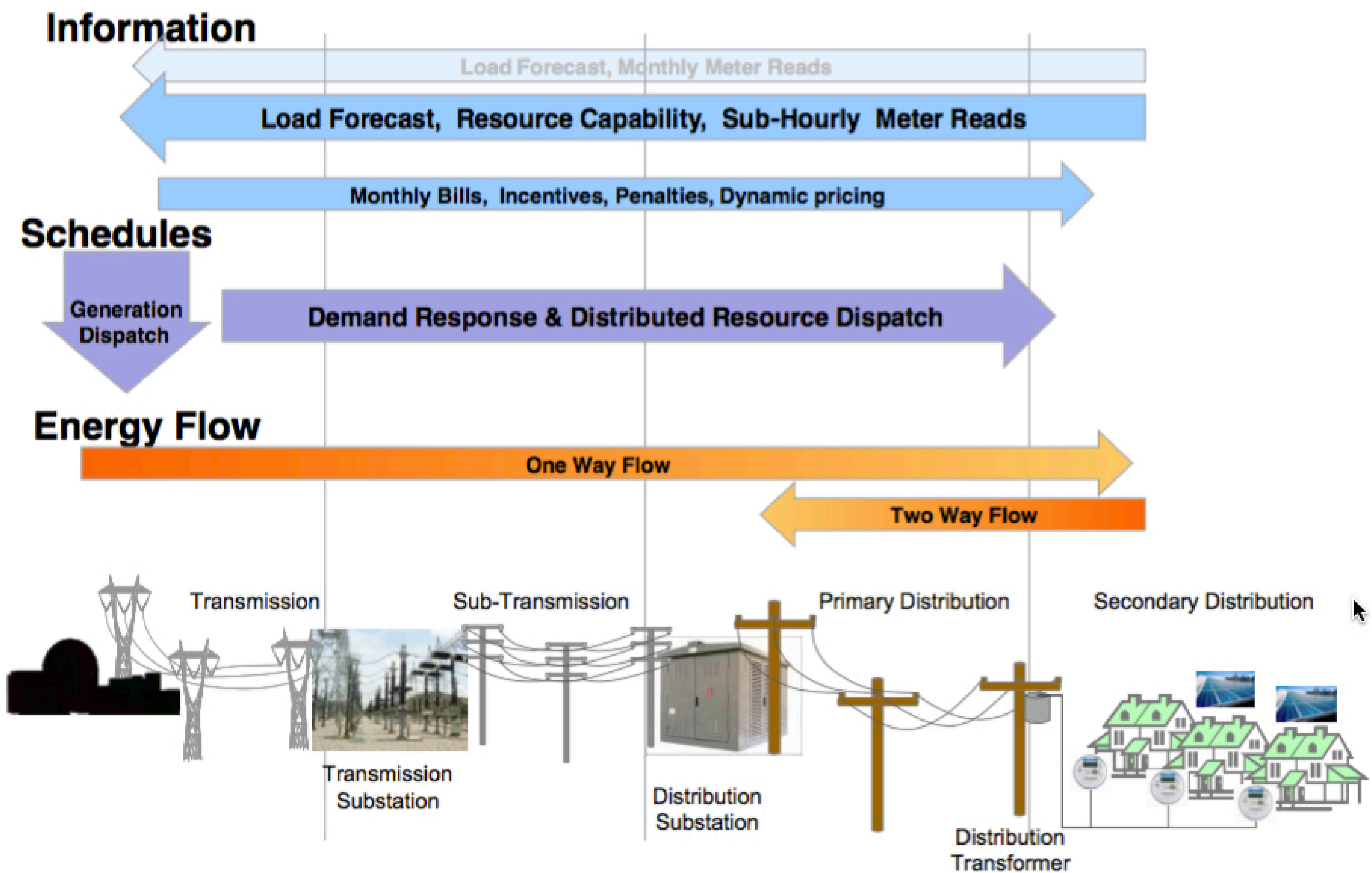
Smart Grid = Electric Grid + Intelligence



Conventional Operation

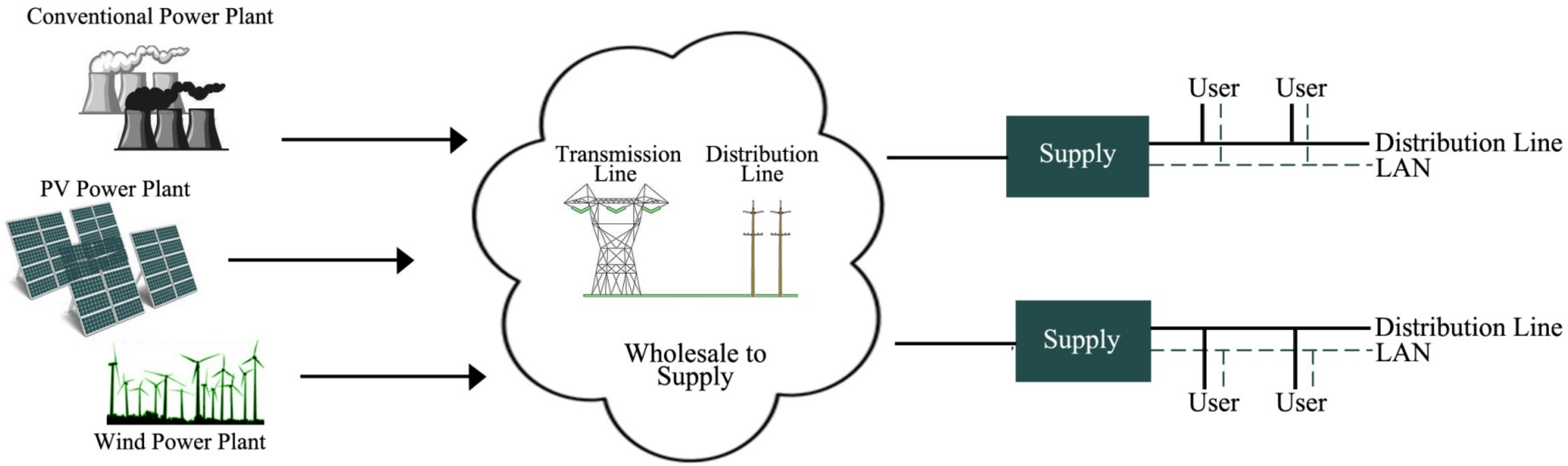


Smart Grid Operation



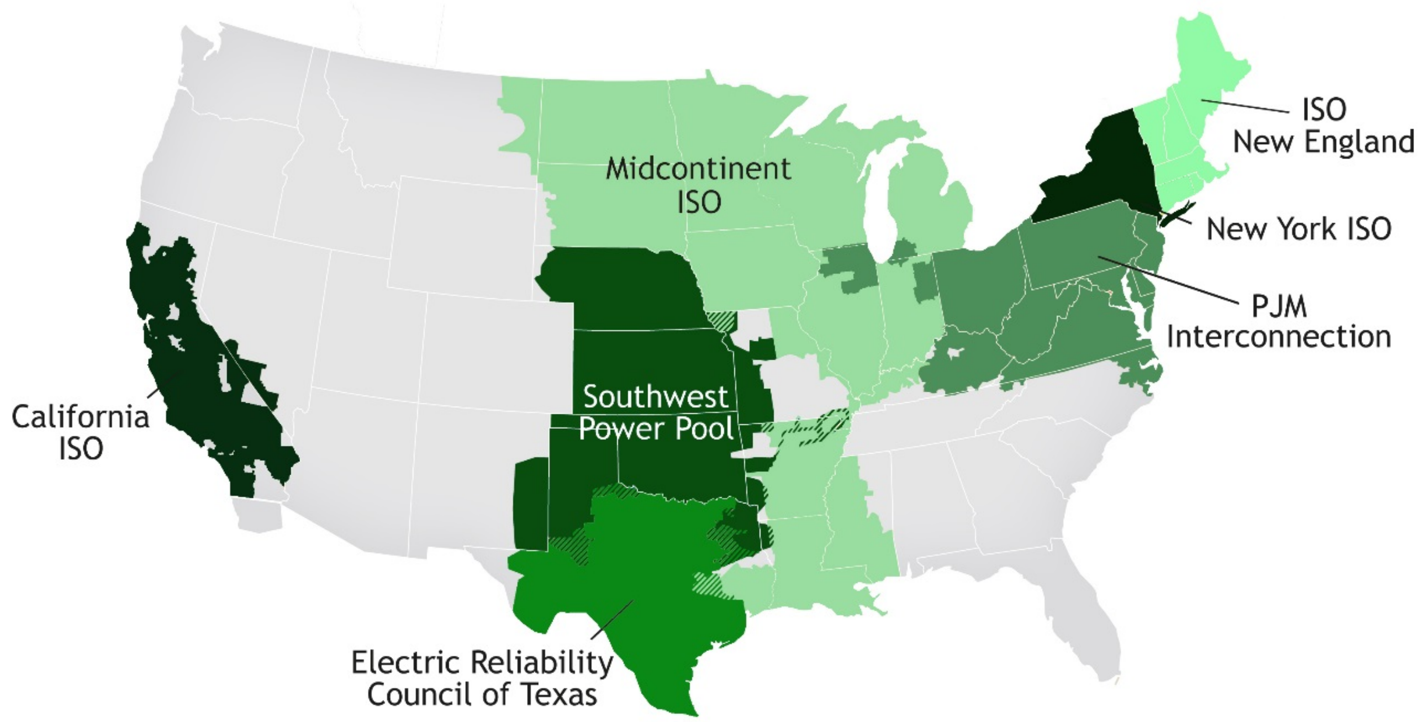
Deregulation of the energy market

- An electricity market is a system enabling purchases, through bids to buy, sales offers to sell; and short-term trades.
- One early introduction of energy market concepts and privatization to electric power systems took place in **Chile in early 1980s**.



Overview of Power Markets

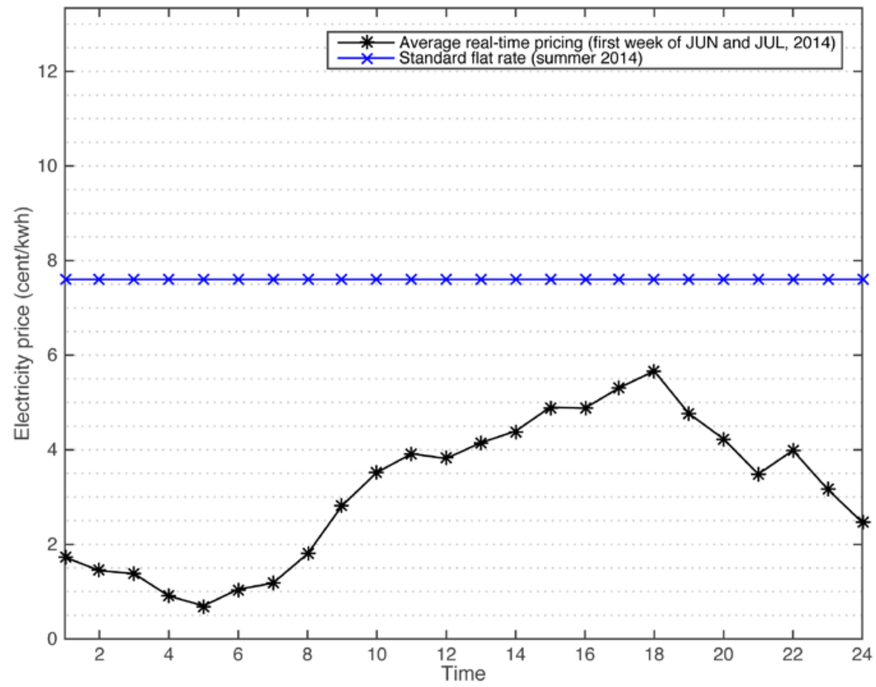
- **Independent System operator (ISO)** and **Regional Transmission Organization (RTO)** coordinate generation and transmission across wide geographic regions, matching generation to the load instantaneously to keep **supply and demand for electricity in balance.**



Power Markets

❖ The power market has introduced several pricing models:

- Flat Rate
- Dynamic Pricing (Real-time pricing (RTP) – Day ahead Pricing)

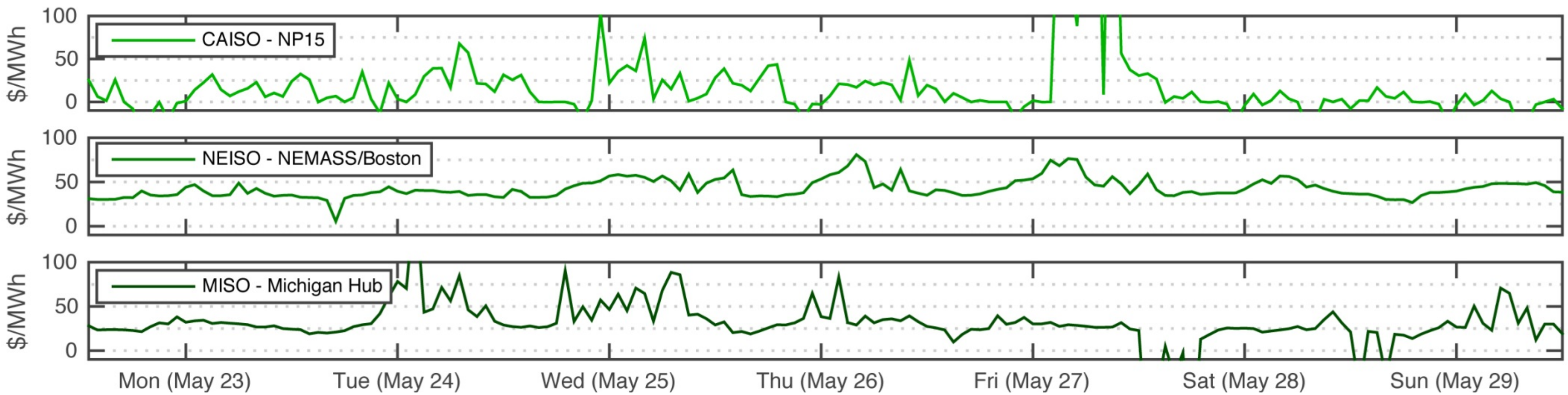


Midcontinent ISO (April 27, 2015)

Real-time Electricity Pricing (RTP)

- Consumers are charged with different electricity prices **from power market to power market at any given time**, and **from time to time at any given power market.**

Real-time hourly electricity price for the week that started on May 23, 2011 at three different ISOs.



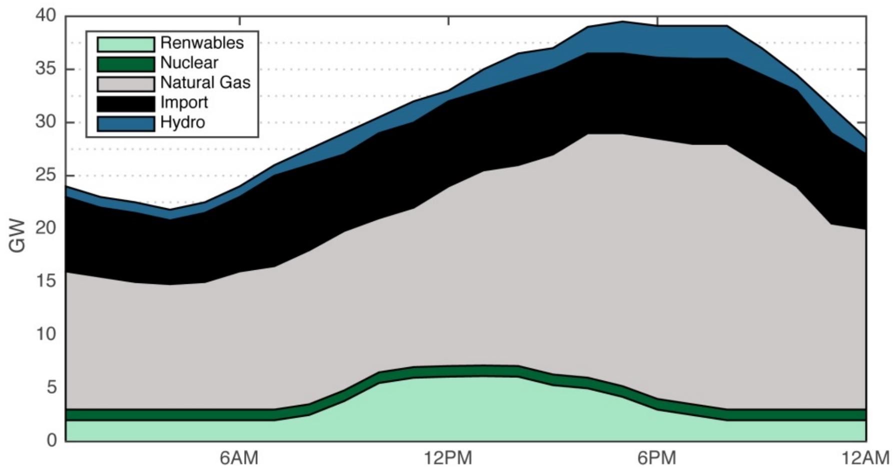
Emissions Factor

❖ The power market **emissions factor** is a representative value that shows the **quantity of emissions in grams**, if a power market user consumes **1 kWh of energy**.

Grams CO_2e per kWh by generation method.

Source	gCO_2e/kWh
Coal	800 to 1050
Oil	816
Natural Gas	430
Nuclear	6
Hydro	4
Wind power	3 to 22
Photovoltaic Solar	60 to 150

Hourly average breakdown of total electricity generation of CAISO by resource type in October 12, 2015.

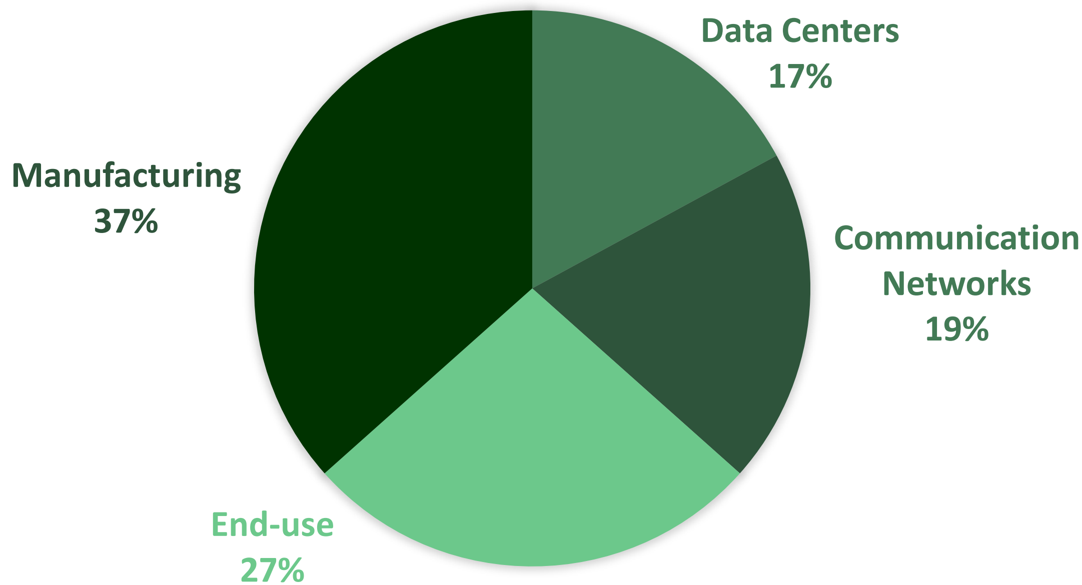


❖ For example:

$$\gamma = \underbrace{0.20 \times 60}_{\textbf{Solar}} + \underbrace{0.05 \times 6}_{\textbf{Nuclear}} + \underbrace{0.4 \times 430}_{\textbf{Natural Gas}} + \underbrace{0.25 \times 800}_{\textbf{Coal}} + \underbrace{0.15 \times 4}_{\textbf{Hydro}} = \mathbf{384.9}\ gCO_2/kWh$$

Where electricity is used in the ICT ecosystem

- There are four main energy-consuming features of the ICT ecosystem:
  - Public and private **data centers** which store, route and process information
  - Wired, private and public **network**, including cellular, Wi-Fi, and fiber.
  - **End-user equipment** in homes , offices factories and farms
  - **Factories that manufacture all the ICT equipment.**



Energy Consumption in the Core network

- Core network (backbone) Consume 11 million metric tons GHG emissions annually, equivalent to Massachusetts power plants emissions 2014.
- Even small cost saving can fluctuate the expenditures on the scale of millions of dollar per year.

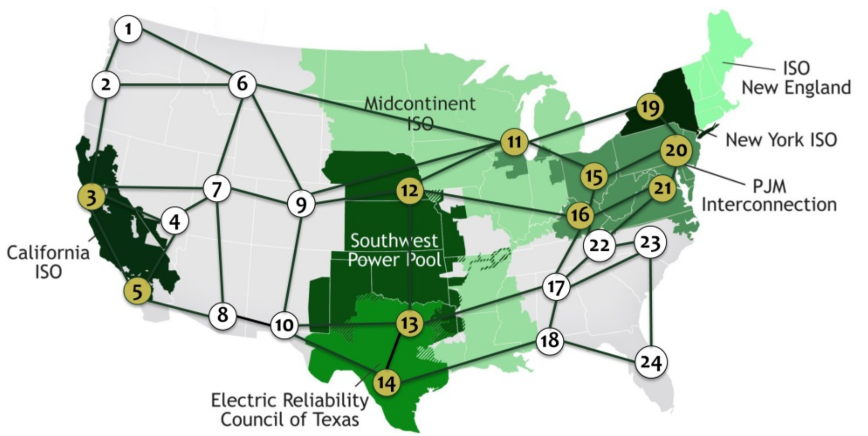
	Energy (TWh/yr)	Electricity Cost ($/yr)	Emission (Mt/yr)
Manufacture	330	19.8B	174
Use:	1170	70.2B	615
Telecommunication Net.:	435	26.1B	229
Backbone	20	1.2B	11
Access Network	280	16.8B	147
Aggregation	40	2.4B	21
Mobile Access	95	5.7B	50
Data Centers:	165	9.9B	87
CPU	70	4.2B	37
DRAM	20	1.2B	11
Disks	20	1.2B	11
Networking	10	600M	5
Misc.	5	300M	3
Power Overhead	15	900M	8
Cooling Overhead	25	1.5M	13
End-Use	570	34.2B	300
Total:	1500	90B	789

Power Markets

- While many consumers on electric grid can shift their consumption in **time, only ICT** can shift their consumption in **space.**

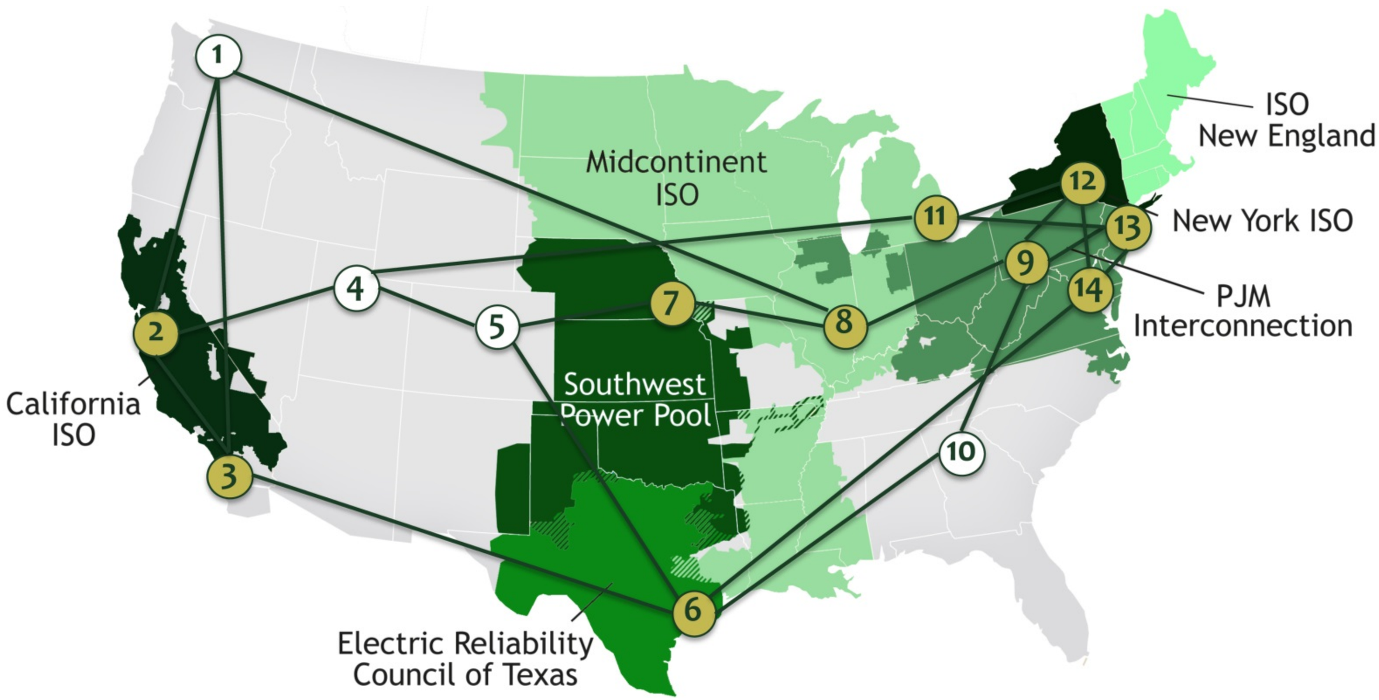
- Networks span areas as large as continent and are therefore:
  - Served by multiple utility companies
  - Different time zones across the network

- Regions can be classified as one of two types:
  - Regions those **are not located** in any power markets;
  - Regions those **are located** in zone with power energy markets



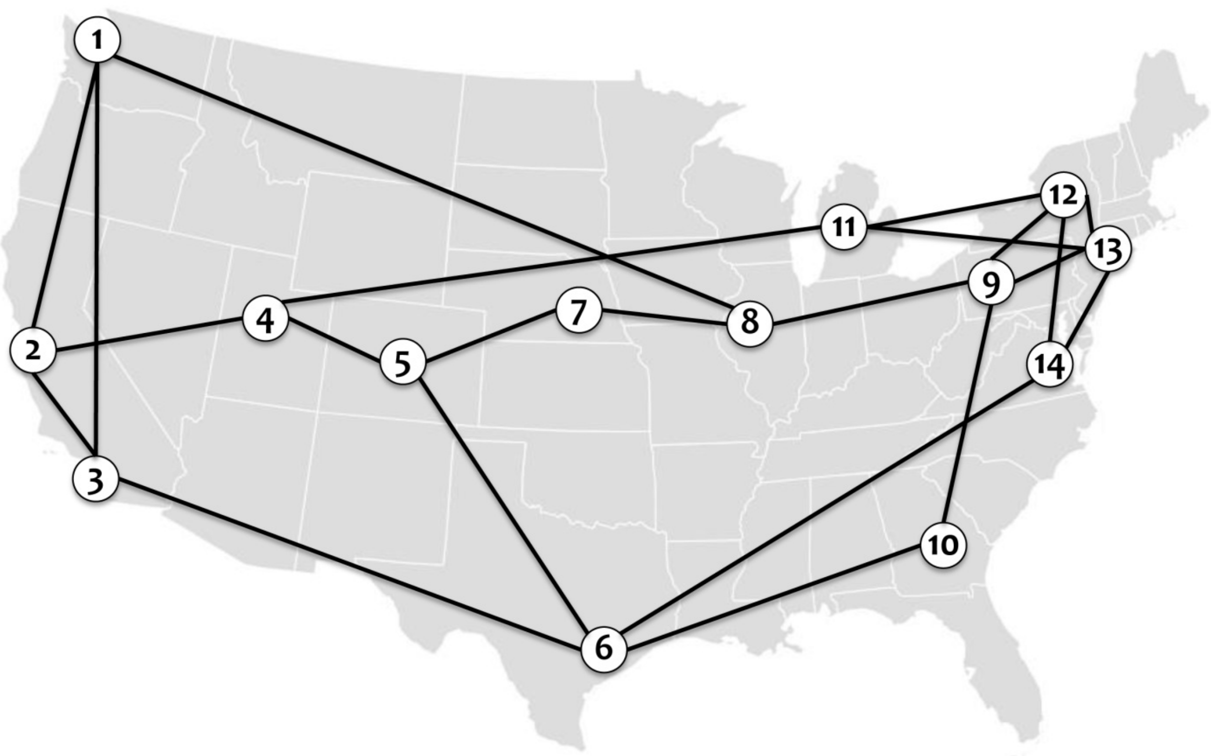
Power Markets

❖ Network nodes can be classified as one of two types:
  - **FR-nodes (Flat Rate Nodes):** nodes that are not located in any power markets.
  - **RT-nodes (Real Time Nodes):** nodes have access to the power markets in their regions.



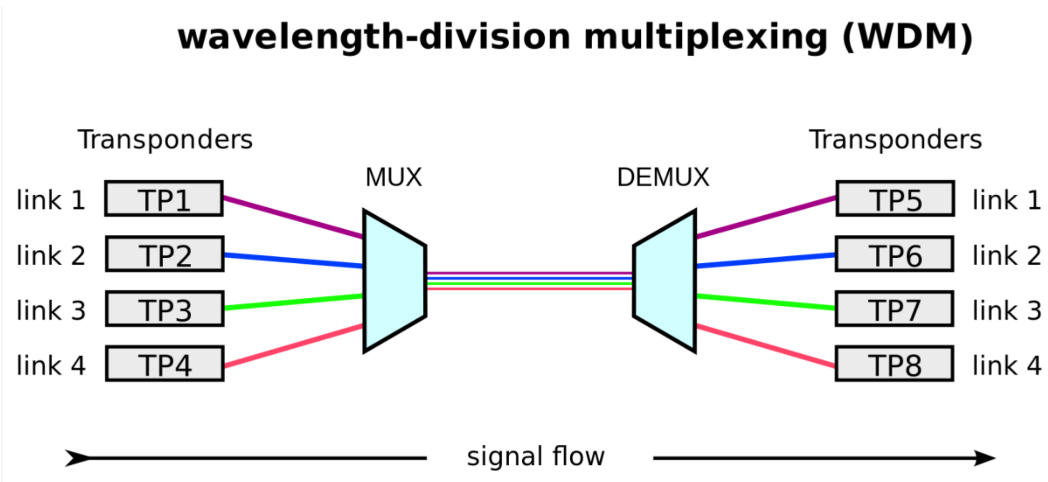
Core Networks

❖ A core network is a part of communication networks that interconnects various **core routers** on the Internet, **providing a path** for exchange of information between different subnetworks.

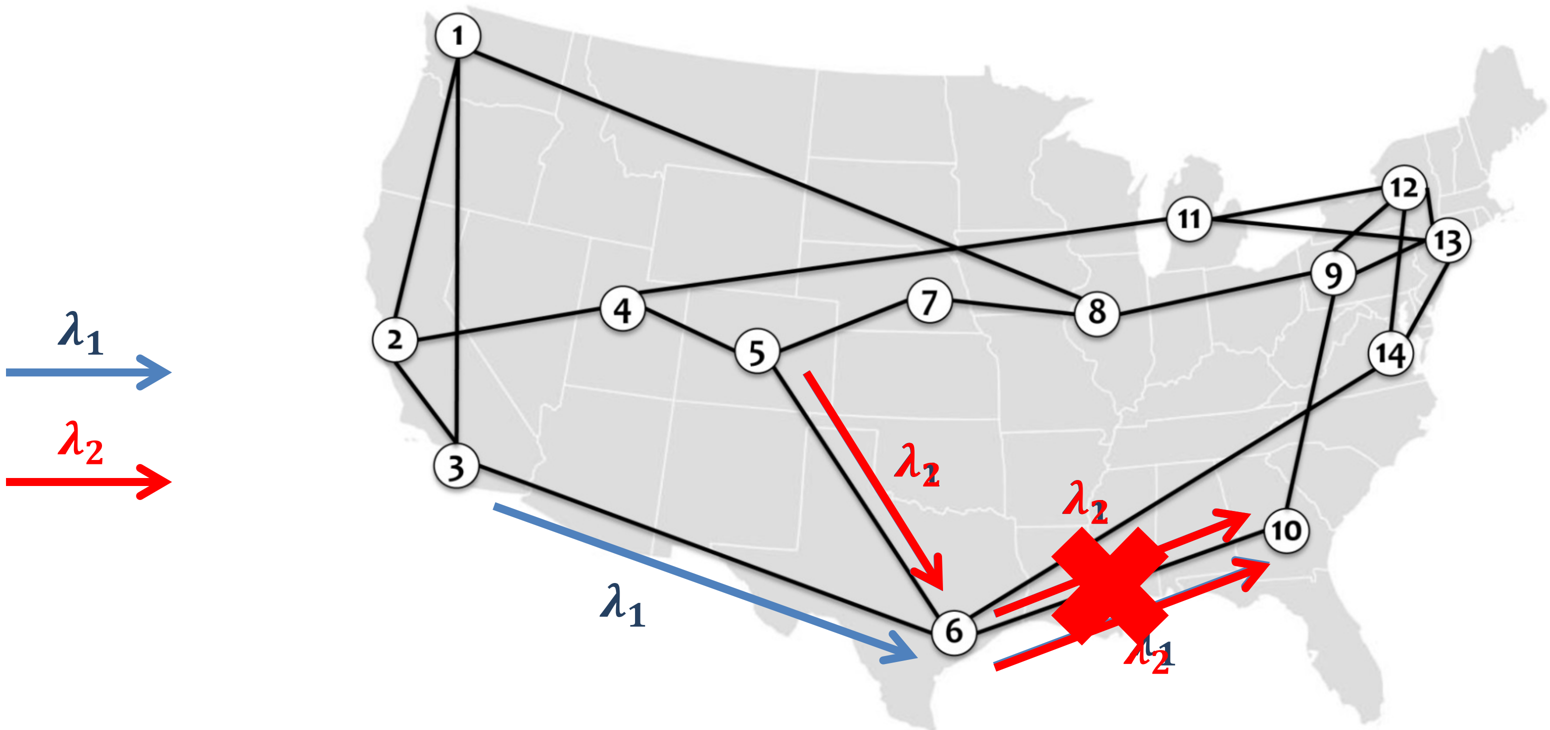


Overview of Optical Communication

- We consider an IP-over-WDM multilayer network model for core networks.
- Bandwidth broken up into fixed-sized wavelengths (λ)
- Pack multiple wavelengths onto the same optical fiber.



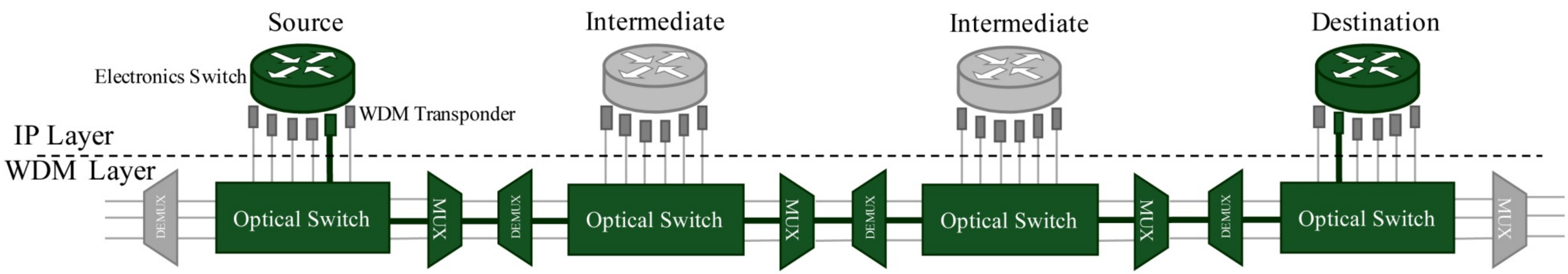
- Lightpath: Route + Wavelength
- Wavelength Continuity Constraint (WCC)
- Wavelength Clash Constraint



Multilayer End to End Network Architecture

❖ Comprehensive multilayer model to calculate nodal power consumption.

❖ Conversions
- ➢ Source : Electrical ⟶ Optical
- ➢ Intermediate: Optical
- ➢ Destination: Optical ⟶ Electrical



Nodal Power Model

$$p_{IP} = \pi_{IP}(A_{IN} + A_{OUT} + r(L_D + L_A))$$
$$p_{OEO} = \pi_{TX}(r)(L_D + L_A)$$
$$p_{WDM} = \pi_{OXC}(L_D + L_A) + \alpha(L_{IN} + L_{OUT}) + \beta$$

- At Source or Destination node:

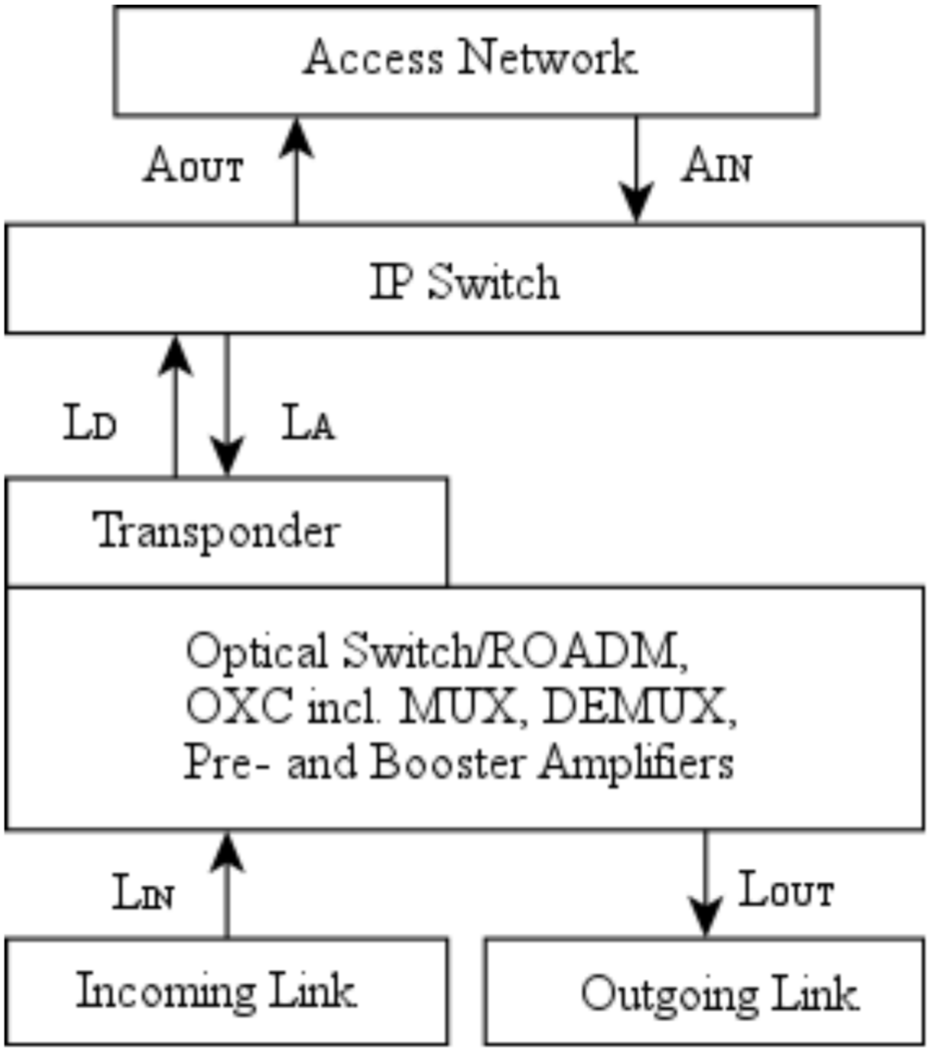
$$p_{node} = p_{IP} + p_{OEO} + p_{WDM}$$

- At Intermediate node:

$$p_{node} = p_{WDM}$$

- Energy Consumption:

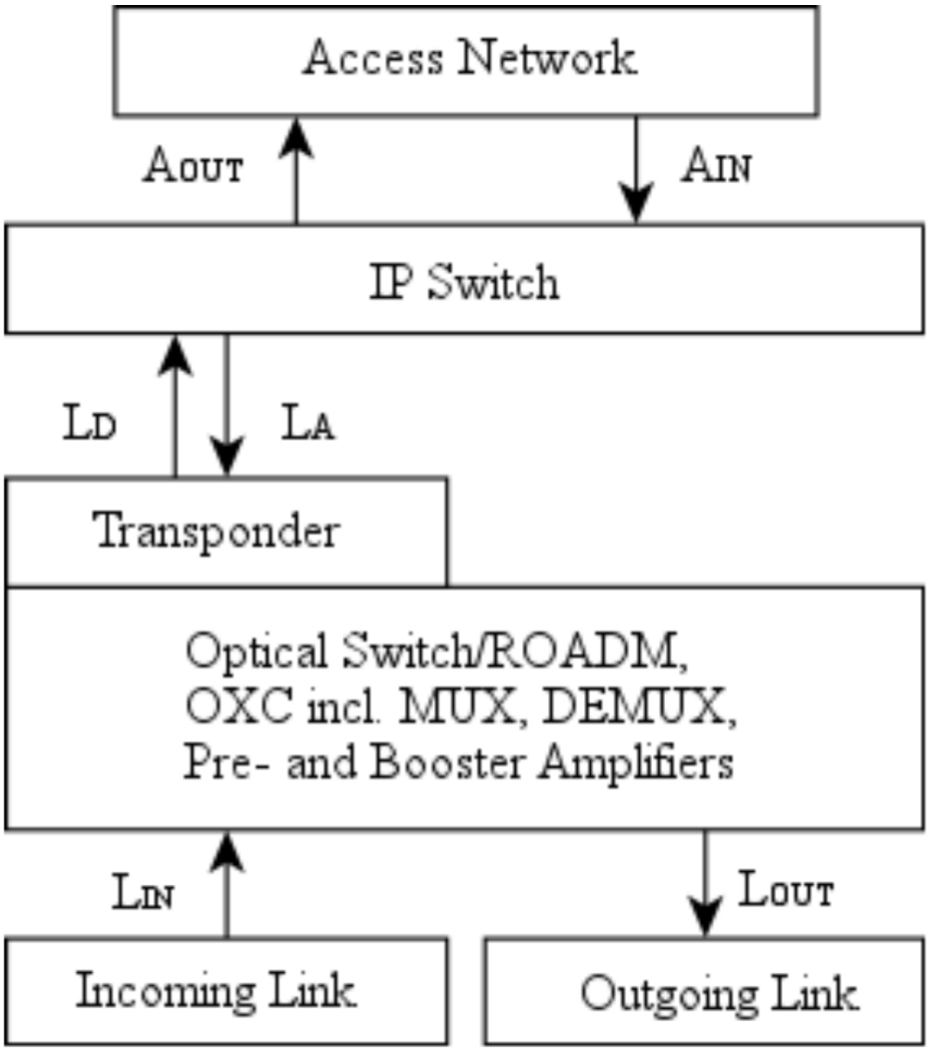
$$E_{node} = p_{node} \times t_{service}$$



Nodal Power Model

Symbol	Description	Unit
A_{IN}	Input traffic from access network	*Gbps*
A_{OUT}	Output traffic to access network	*Gbps*
L_{D}	Lightpaths dropped from WDM to IP (O-E)	integer
L_{A}	Lightpaths added to WDM from IP (E-O)	integer
L_{IN}	Incoming lightpaths	integer
L_{OUT}	Outgoing lightpaths	integer

Symbol	Description	Value	Unit
r	Transponder transmission rate	10	*Gbps*
$\pi_{\mathrm{TX}}(r)$	Transponder power consumption	0.05	kW
π_{OXC}	OXC power consumption	0.1	kW
π_{IP}	IP layer power consumption	0.01	$kW/Gbps$



Routing Variations - Anycast

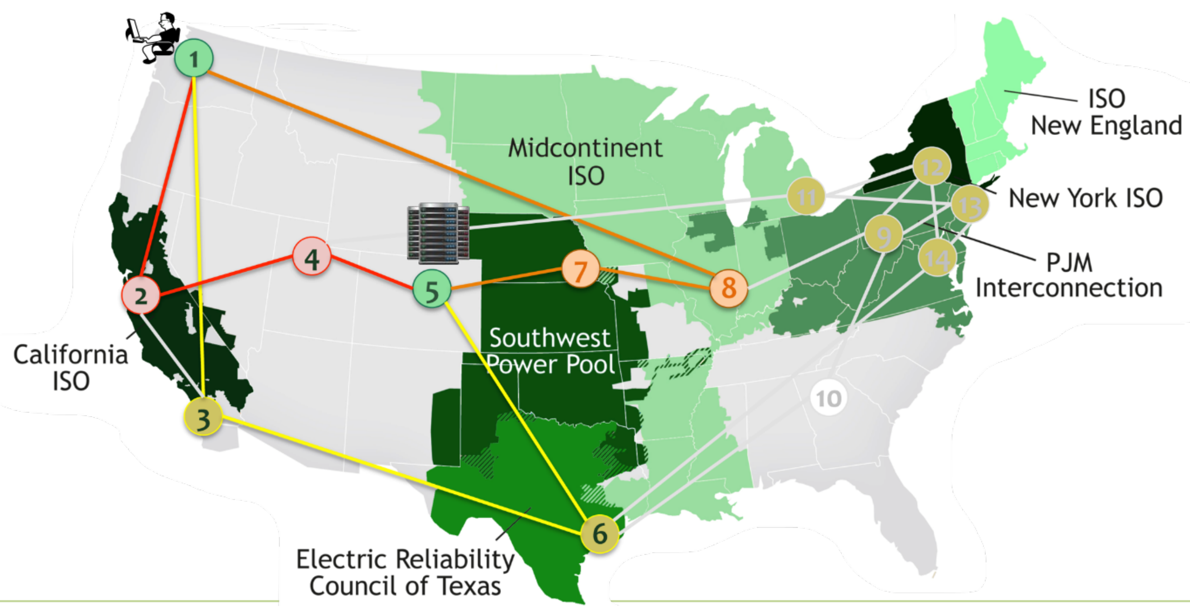
- The request can be handled by any of the available destinations.
- Anycasting is known to improve network resource allocation efficiency when compared to inflexible pre-determined unicast lightpaths.
- Dijkstra Shortest-hop path is calculated to reach each candidate destination.

Energy Aware Routing

- An algorithm to find the approach to transfer data between two sites based on the energy information: ***Energy Aware Routing***.

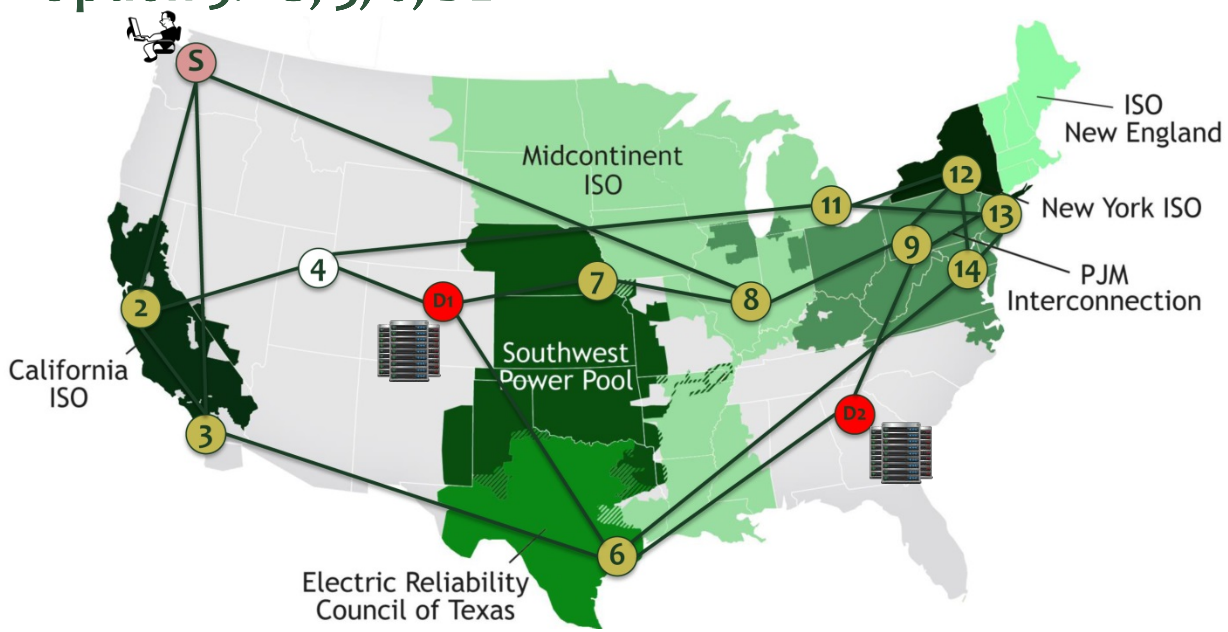
- We evaluate our Algorithms **Least Dollar Path (LDP)** and **Least Emissions Path (LEP)** compare its result with
  - **Shortest Hop Path (SHP)**
  - **Shortest Distance Path (SDP)**

- **Final Route:**
  - **SHP:** <1, 2, 4, 5>
  - **SDP:** <1, 2, 4, 5>
  - **LDP:** *Dynamic*
  - **LEP:** *Dynamic*



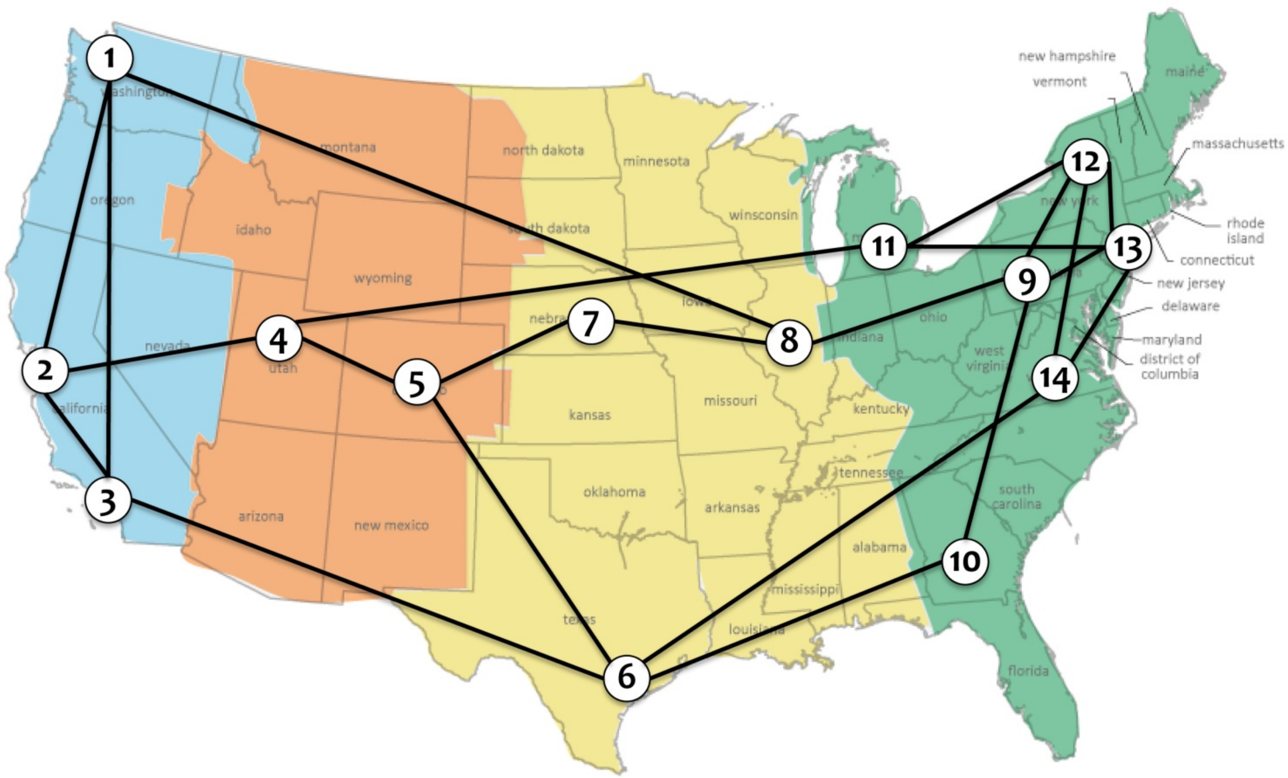
Anycast Example

- There are five different paths for transferring data between nodes ***Seattle, WA (S)*** to ***Boulder, CO (D1)*** *or* ***Atlanta, GA (D2)***:
  - **Option 1: <*S, 2, 4, D1*>**
  - **Option 2: <*S, 3, 6, D1*>**
  - **Option 3: <*S, 8, 7, D1*>**
  - **Option 4: <*S, 8, 9, D2*>**
  - **Option 5: <*S, 3, 6, D2*>**



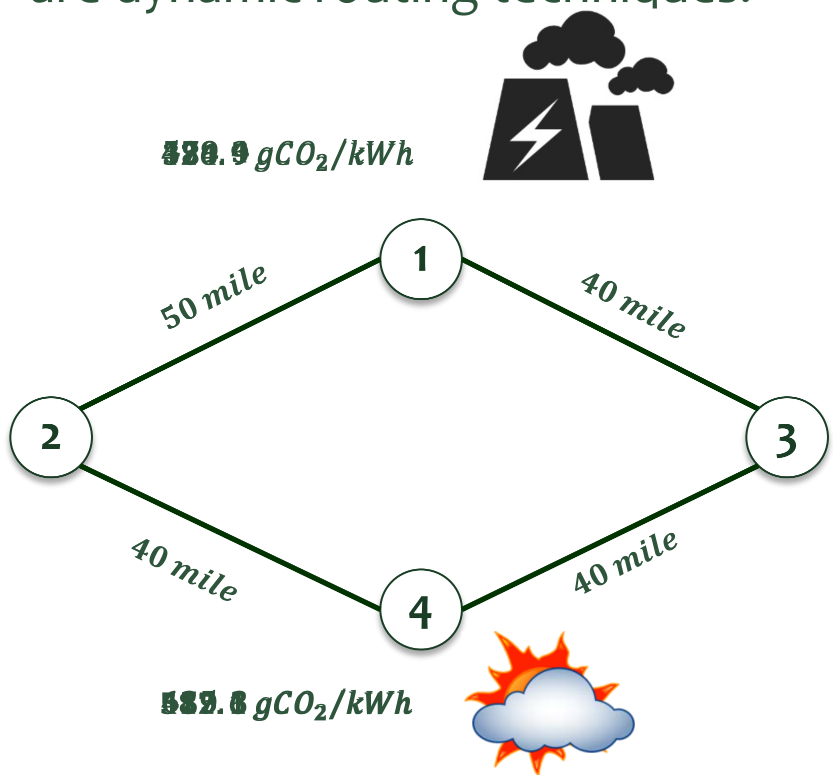
Multi Time-Zone Region

- A large network may be distributed across multi time-zone country, region or continent.
- Various time zones leads to various peak and off-peak hour among nodes.



Dynamic Routing

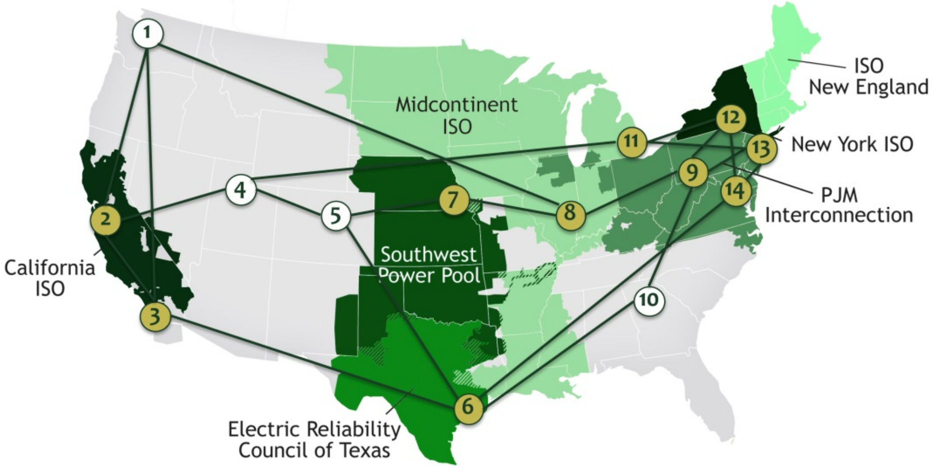
➢ LEP and LDP are dynamic routing techniques.

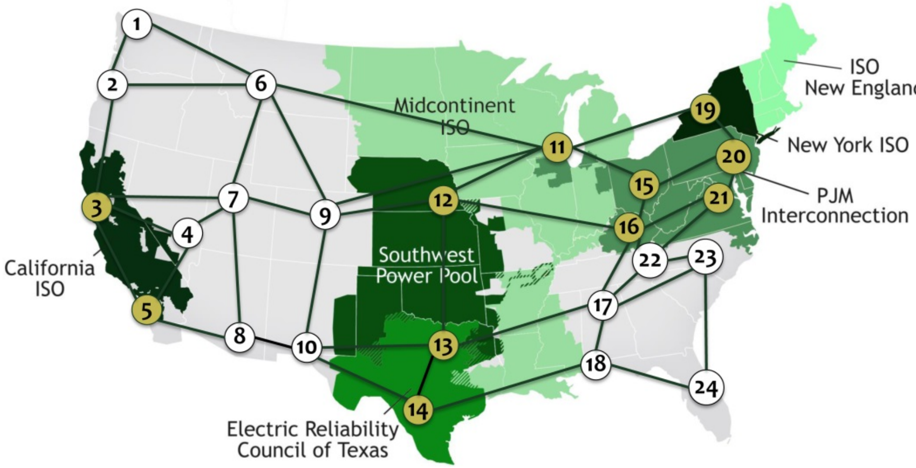


❖ The dynamic routing calculation changes the weight of each link every ***t*** units of time.

Network Assumption

- Topologies:
  - 24-node USnet
  - 14-node NSFnet
- Algorithms:
  - LEP (Least Emissions Path)
  - LDP (Least Dollar path)
  - SHP (Shortest Hop Path)
  - SDP (Shortest Distance Path)

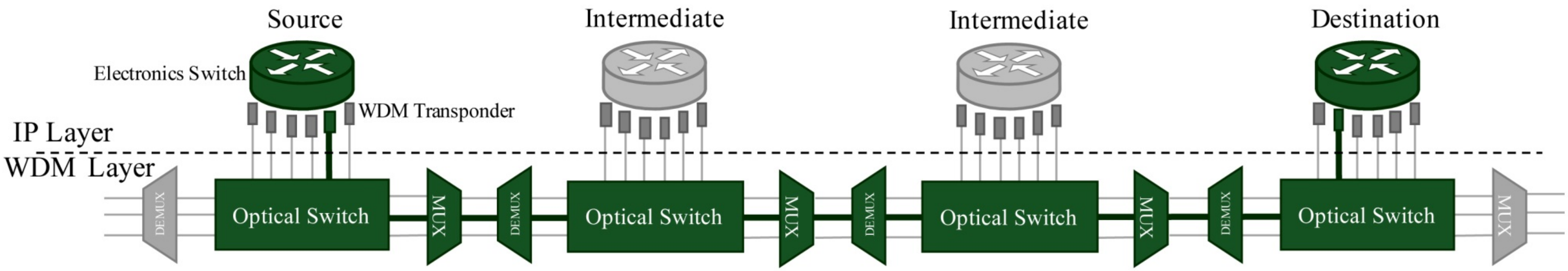




Unicast Simulation

- The link weight, $W_{i,j}$, for LDP, and LEP :
  - **LDP:** $W_{i,j} = C_j$
  - **LEP:** $W_{i,j} = \Gamma_j$

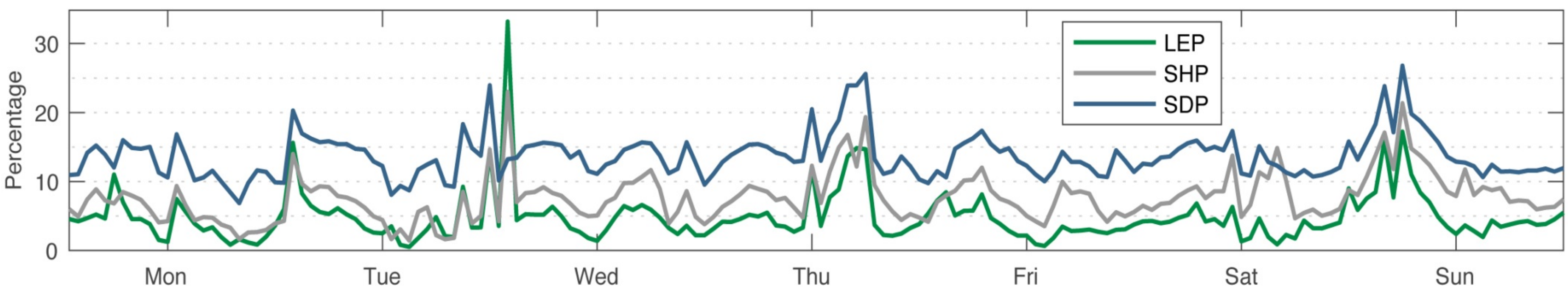
- Power Consumption:
  - If $\boldsymbol{n}$ is a source or a destination: $\boldsymbol{P^n} = p_{ip} + p_{OEO} + p_{WDM}$
  - If $\boldsymbol{n}$ is a intermediate node: $\boldsymbol{P^n} = p_{WDM}$



Unicast Simulation

- Energy Consumption:
  - $E_n = P_n \times t$
- Electricity Cost and Emissions:
  - $C_n = E_n \times EP_n$
  - $\Gamma_n = E_n \times \gamma_n$
- The **LDP** Improve:
  - **LEP:** 4.33% (Max: 34%)
  - **SHP:** 5.13% (Max: 24%)
  - **SDP:** 7.17% (Max: 26%)

LDP Cost improvement in 24-node USnet.

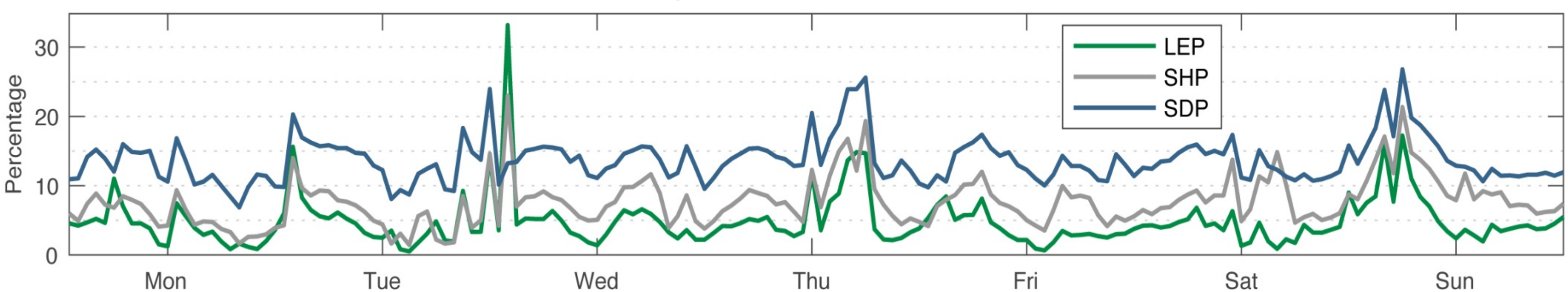


LDP Unicast Simulation

- A higher gap between electricity price causes the higher electricity cost improvements.

- There are three reasons for big gap among nodal electricity prices:
  - Different time zones
  - Flat rate electricity price is independent of electricity market conditions
  - The spike increases the gap.

LDP Cost improvement in 24-node USnet.

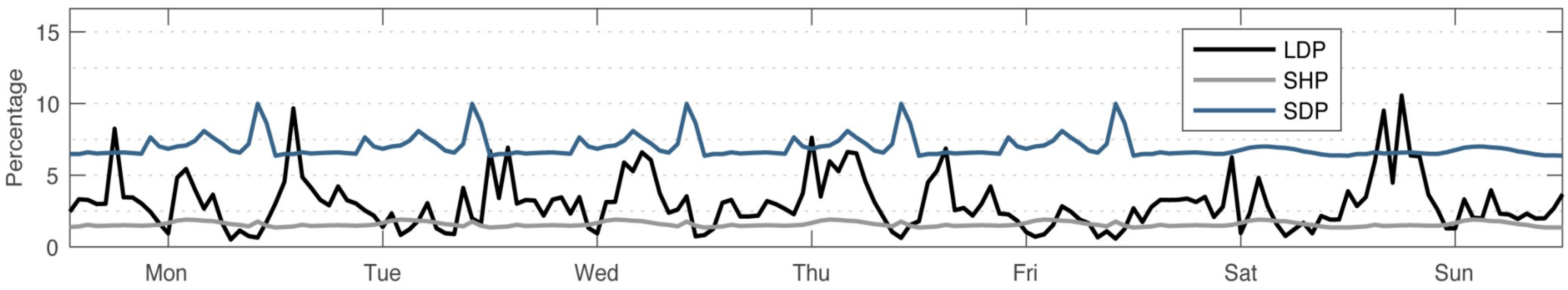


LEP Unicast Simulation

- The **LEP** Improve:
  - **LDP:** 3.19% (Max: 11%)
  - **SHP:** 2.15% (Max: 4%)
  - **SDP:** 3.70% (Max: 10%)

- There are three reasons for big gap among nodal electricity prices:
  - Different time zones
  - LEP is unable to track the emissions factor of FR-nodes.
  - Regional natural disasters.

LEP Emissions improvement in 24-node USnet.



Anycast Simulation Algorithms

- Adding more replicas improves reliability and lower latency, but also increases the total network costs.
- We can define such demand routing as an anycast request.
- Algorithm checks electricity cost/emissions of any destinations.

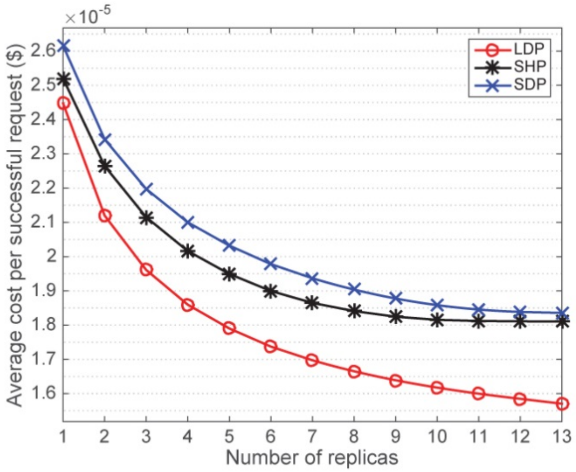
Algorithm 1: Least Emission Path Algorithm

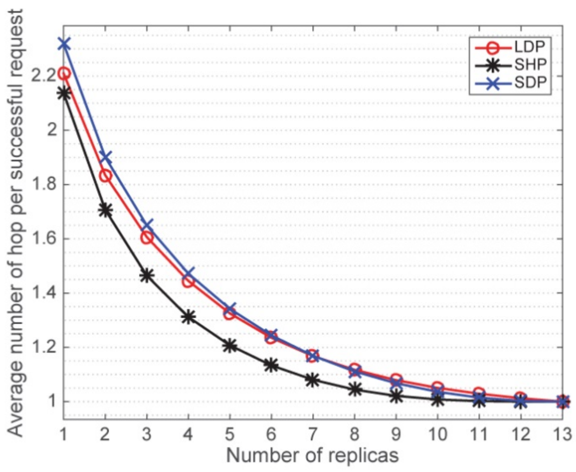
```
input  : Req = (L_r, u, τ)
Γ_min = ∞
p_LEP = φ
for each r ∈ Lr do
    use Dijkstra's algorithm with dollar cost weights
    (Equation (5))
    calculate emissions (Γ_r) of found path p_r by
    Equation (6)
    if Γ_r < Γ_min then
        Γ_r = Γ_min
        p_LEP = p_r
```

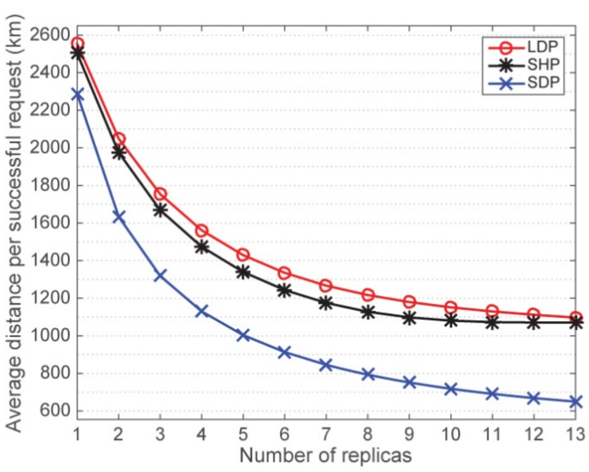
Best Number of Replica

- Five replicas leads to 1.2 hops per request, means a replica is one of the neighbor nodes of user for 83% of requests.

- When the number of replica is increased:
  - From 1 to 2: 11.3% electricity cost saving
  - From 2 to 3: 6.8% electricity cost saving
  - From 3 to 4: less than 5% improvements.

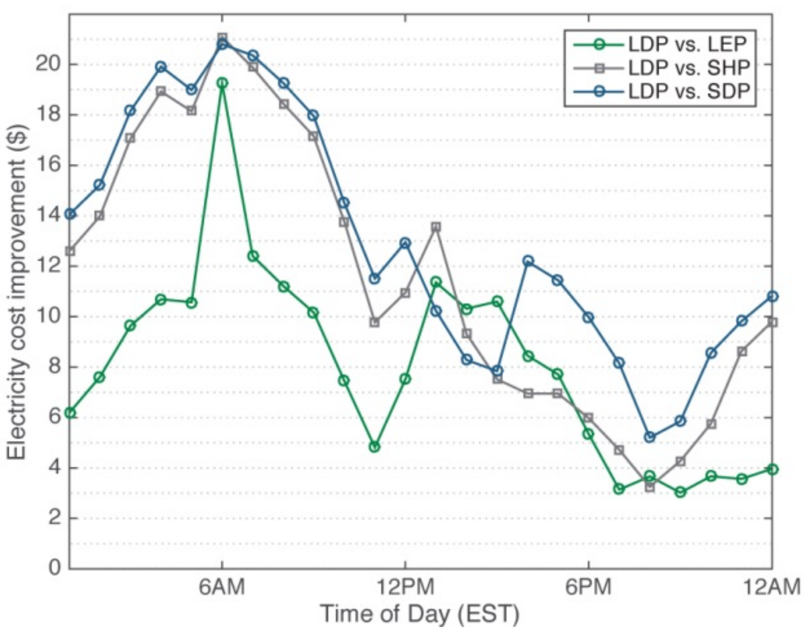


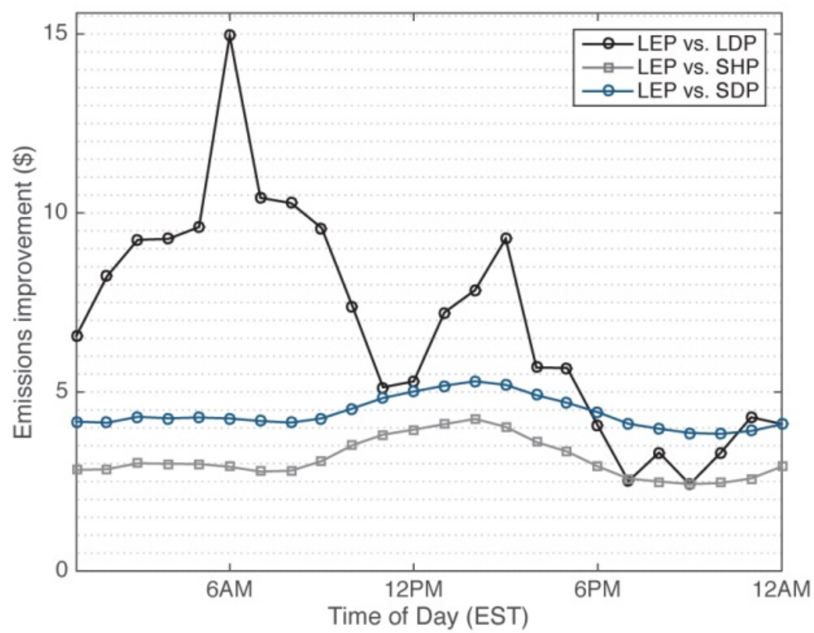




Anycast Simulation Results

- **High Improvement during morning hours:**
  - Different peak and off-peak hour for nodes of the networks.
  - Lowing electricity price of nodes that are charged with real-time pricing in night.

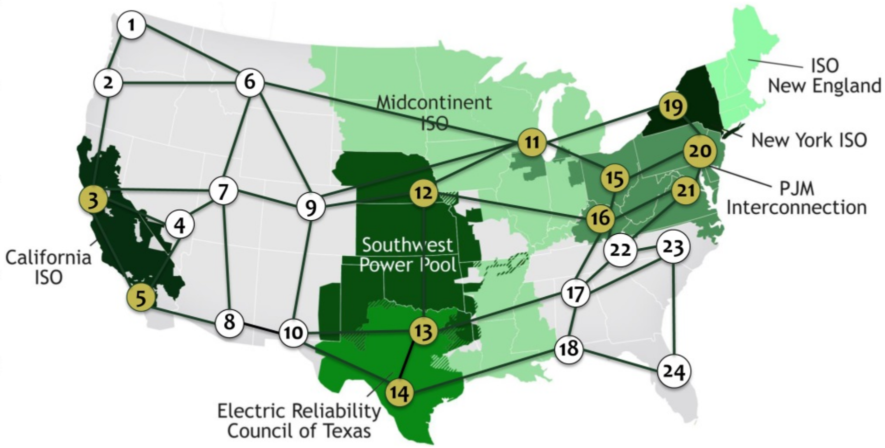




Best and Worst Replicas Locations

- Investigating all 2024 possible combinations for three replicas.
- Better to use the RT-nodes as a replica set.
- Better to distribute across the networks

		Emissions (kg)		Electricity Cost ($)	
		Replicas	Value	Replicas	Value
LDP	Best	[3,13,15]	1591.6	[3,13,11]	242.3
	Worst	[1,2,4]	1709.5	[4,5,8]	260.96
LEP	Best	[3,13,16]	1586.0	[3,11,14]	246.9
	Worst	[18,23,24]	1683.1	[4,5,8]	264.77
SHP	Best	[3,14,16]	1587.0	[3,11,14]	246.6
	Worst	[1,2,4]	1705.1	[4,5,8]	262.50
SDP	Best	[5,14,16]	1589.9	[3,11,14]	247.7
	Worst	[1,2,4]	1696.7	[1,2,4]	262.15



Simulation Disadvantages

- Time interval is based on the contract between consumer and power distribution company.
- Typical intervals late:
  - 1 hour
  - 15 minutes
  - 5 minutes.
- Simulation methods are really time consuming.
- Analytical model should be able to calculate electricity cost and emissions:
  - When the network has lost packets.
  - When the time of service is longer then an hour.

Unicast Analytical Model:

- Each node has three groups of request:
  - **Source Arrival Rate (λ_{nst}):** the traffic that starts from node ***n*** at time interval ***t***.
  - **Intermediate Arrival Rate (λ_{nit}):** the transmit traffic of node ***n*** at time interval ***t***.
  - **Destination Arrival Rate (λ_{ndt}):** the traffic that is destined at the node ***n*** at time interval ***t***.

$$\boldsymbol{\lambda_{ndt} = m_{nt} \times \lambda_t}$$

λ_t : Arrival Rate of Networks

- There is $n(n-1)$ different combinations for the 14-node network .

$$m_{nt} = \frac{U_{nt}}{n(n-1)}$$

Unicast Analytical Model:

- **Holding time ψ (t, h):** the ratio of the generated traffic at time interval **t**, that continues t to time interval **h**.

- Power consumption in node ***n*** at time interval ***h***:

$$P_{nh} = \sum_{t=1}^{h} \psi(t,h)\left[(\lambda_{nst} + \lambda_{ndt})\left(p_{WDM} + p_{OEO} + p_{ip}\right) + \lambda_{nit}\left(p_{WDM}\right)\right]$$

- Total network power consumption:

$$P = \sum_{h=1}^{T}\sum_{n=1}^{N}\sum_{t=1}^{h} \psi(t,h)\left[(\lambda_{nst} + \lambda_{ndt})\left(p_{WDM} + p_{OEO} + p_{ip}\right) + \lambda_{nit}\left(p_{WDM}\right)\right]$$

- Total network power consumption with blocking:

$$P = \sum_{h=1}^{T}\sum_{n=1}^{N}\sum_{t=1}^{h} \psi(t,h)\left[(1 - BP_{nst})(\lambda_{nst} + \lambda_{ndt})\left(p_{WDM} + p_{OEO} + p_{ip}\right) + (1 - BP_{nit})\lambda_{nit}\left(p_{WDM}\right)\right]$$

Unicast Analytical Model:

- $\boldsymbol{\tau}\ (\boldsymbol{t}, \boldsymbol{h})$: average of holding time at time $\boldsymbol{t}$.

- Total energy consumption:

$$E = \sum_{h=1}^{T}\sum_{n=1}^{N}\sum_{t=1}^{h}\psi(t,h)\big[(1-\ BP_{nst})(\lambda_{nst}+\lambda_{ndt})\big(p_{WDM}+\ p_{OEO}+\ p_{ip}\big) + (1-\ BP_{nit})\lambda_{nit}\ (p_{WDM})\big]\,\tau\ (t,h)$$

- Total electricity cost:

$$C = \sum_{h=1}^{T}\sum_{n=1}^{N}\sum_{t=1}^{h}\{\psi(t,h)\big[(1-\ BP_{nst})(\lambda_{nst}+\lambda_{ndt})\big(p_{WDM}+\ p_{OEO}+\ p_{ip}\big) + (1-\ BP_{nit})\lambda_{nit}\ (p_{WDM})\big]\,\tau\ (t,h)\}\,EP_{nh}$$

- Total environmental emission:

$$\Gamma = \sum_{h=1}^{T}\sum_{n=1}^{N}\sum_{t=1}^{h}\{\psi(t,h)\big[(1-\ BP_{nst})(\lambda_{nst}+\lambda_{ndt})\big(p_{WDM}+\ p_{OEO}+\ p_{ip}\big) + (1-\ BP_{nit})\lambda_{nit}\ (p_{WDM})\big]\,\tau\ (t,h)\}\,\gamma_{nh}$$

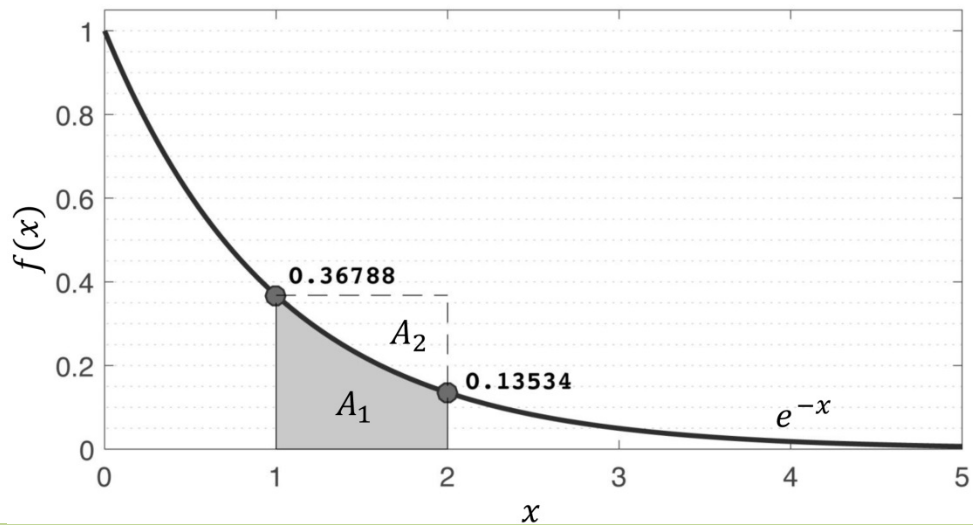
Unicast Analytical Model:

- $\boldsymbol{\tau}$ $(\boldsymbol{t}, \boldsymbol{h})$**:** average of holding time at time **t**.

$$\tau\,(t,h) = \frac{t_i\ \int_h^{h+t_i} f(x-t+1)dx}{f(t)}$$

- **Holding time** $\boldsymbol{\psi}$ $(\boldsymbol{t},\boldsymbol{h})$: the ratio of the generated traffic at time interval **t**, that continues *t* to time interval ***h***.

$$\psi\,(t,h) = \frac{f(h-t+1)}{f(0)}$$



Unicast Analytical Results:

- Results for any time interval in just **3.26** seconds.

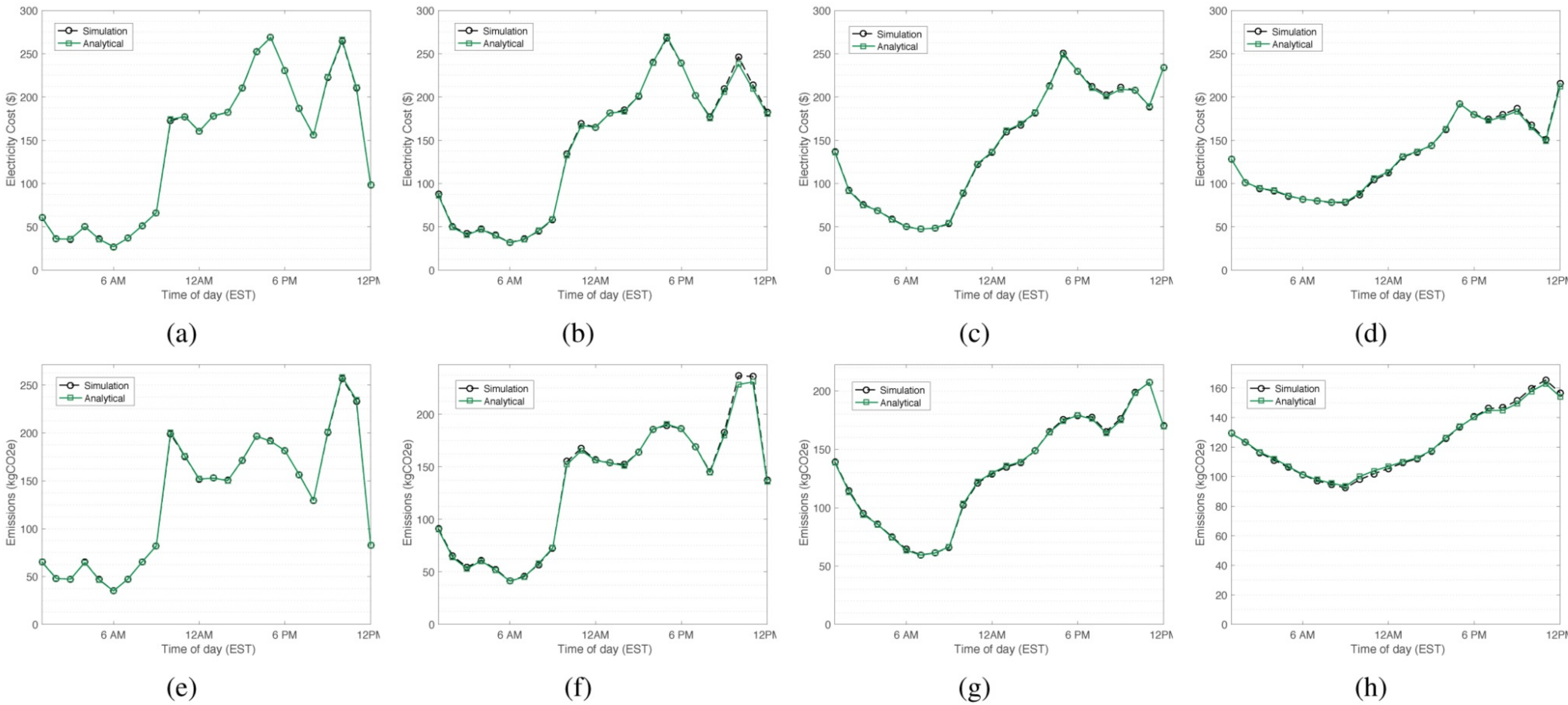


Fig. 9: Electricity cost in 24-node USnet with LDP with (a) 1 minute holding time in the average, (b) 1 hour holding time in the average, (c) 3 hours holding time in the average, (d) 12 hours holding time in the average, and Emissions in 24-node USnet with LDP with (e) 1 minute holding time in the average, (f) 1 hour holding time in the average, (g) 3 hours holding time in the average, and (h)12 hours holding time in the average.

Balanced Cost Path

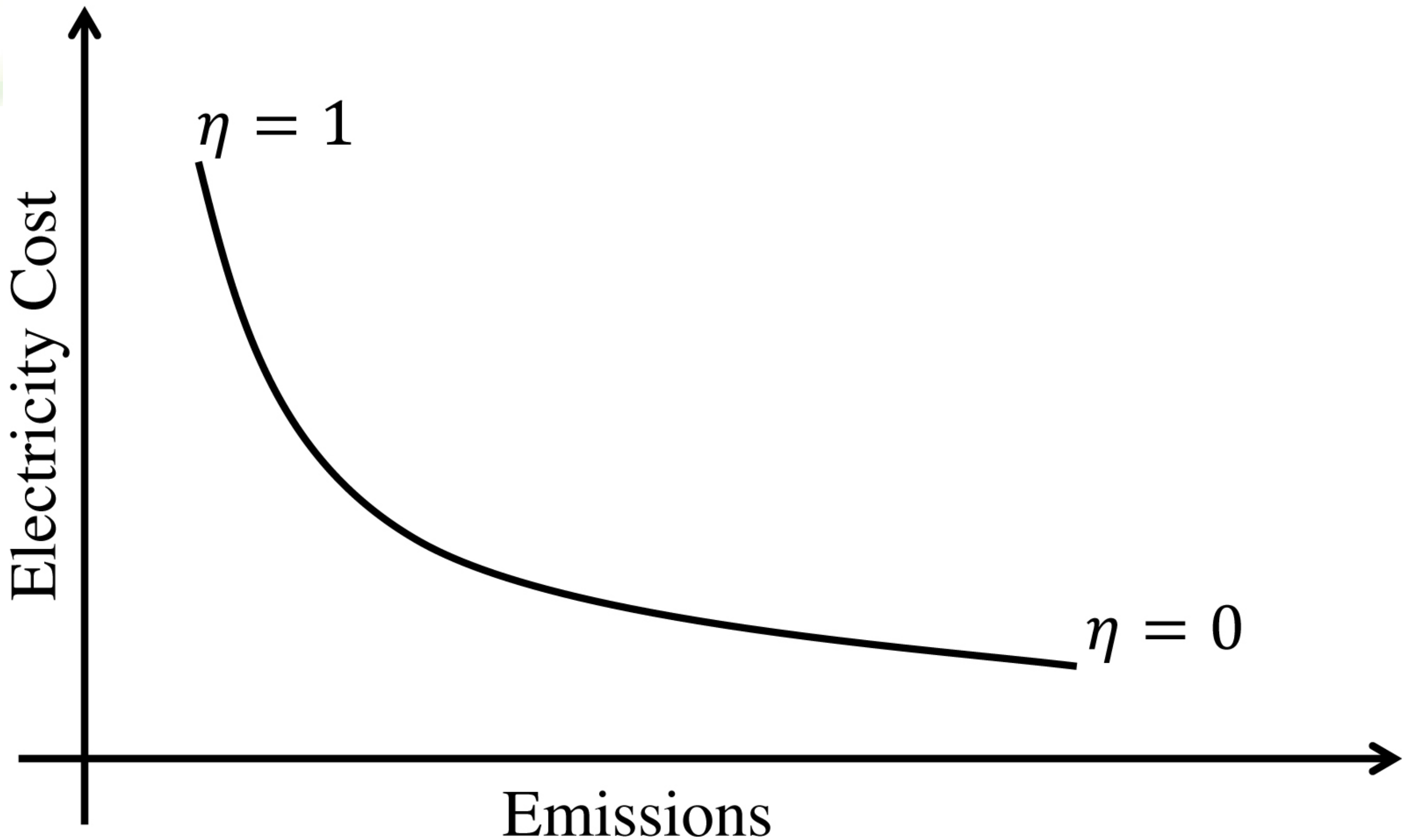
- Some types of conventional power plants are cheap, but they are also the world's top contributing sources of emissions.

- Reduction of LDP and LEP may be distinct goals in opposition to one another.

- Balance Cost Path (BCP) can trade off between electricity cost and emissions.

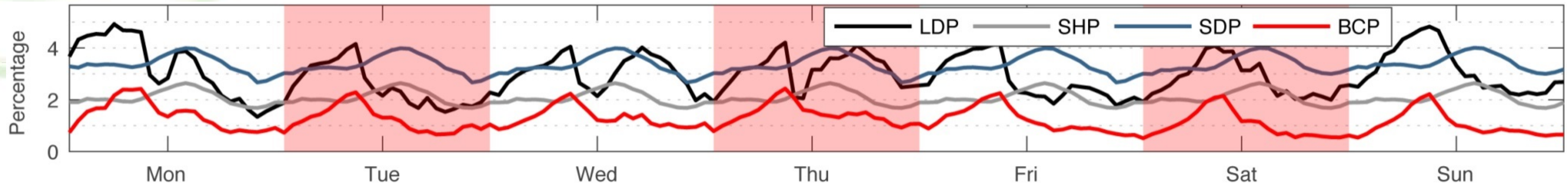
$$W_{i,j} = \eta \frac{C_j}{C_{max}} + (1-\eta)\frac{\Gamma_j}{\Gamma_{max}}$$

Balanced Cost Path

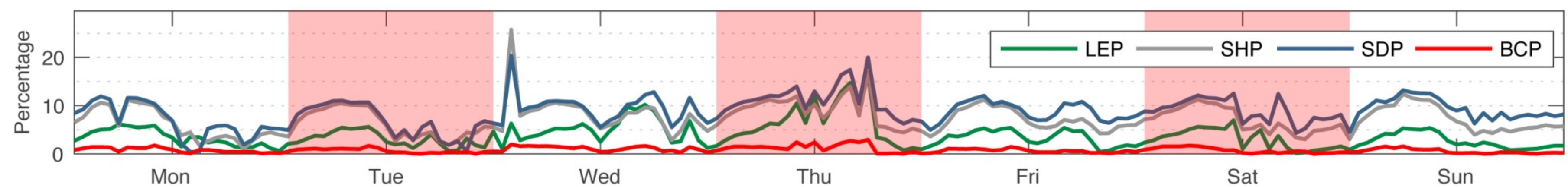


Balanced Cost Path

LDP Cost improvement in 24-node USnet.



LEP Emissions improvement in 24-node USnet.



Balanced Cost Path

Objective Function:

minimize:

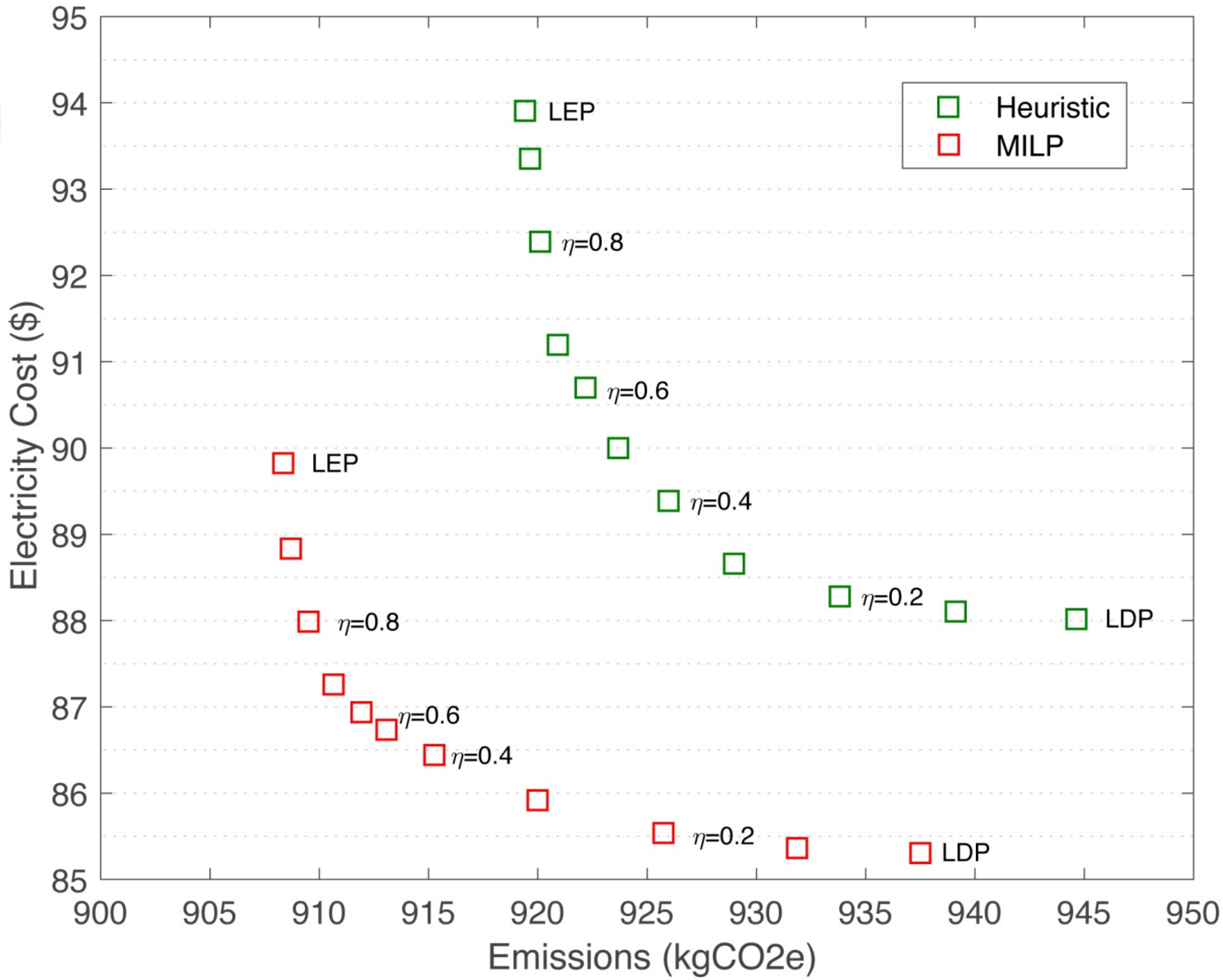
$$\sum_{r}^{R} BC^r$$

Where:

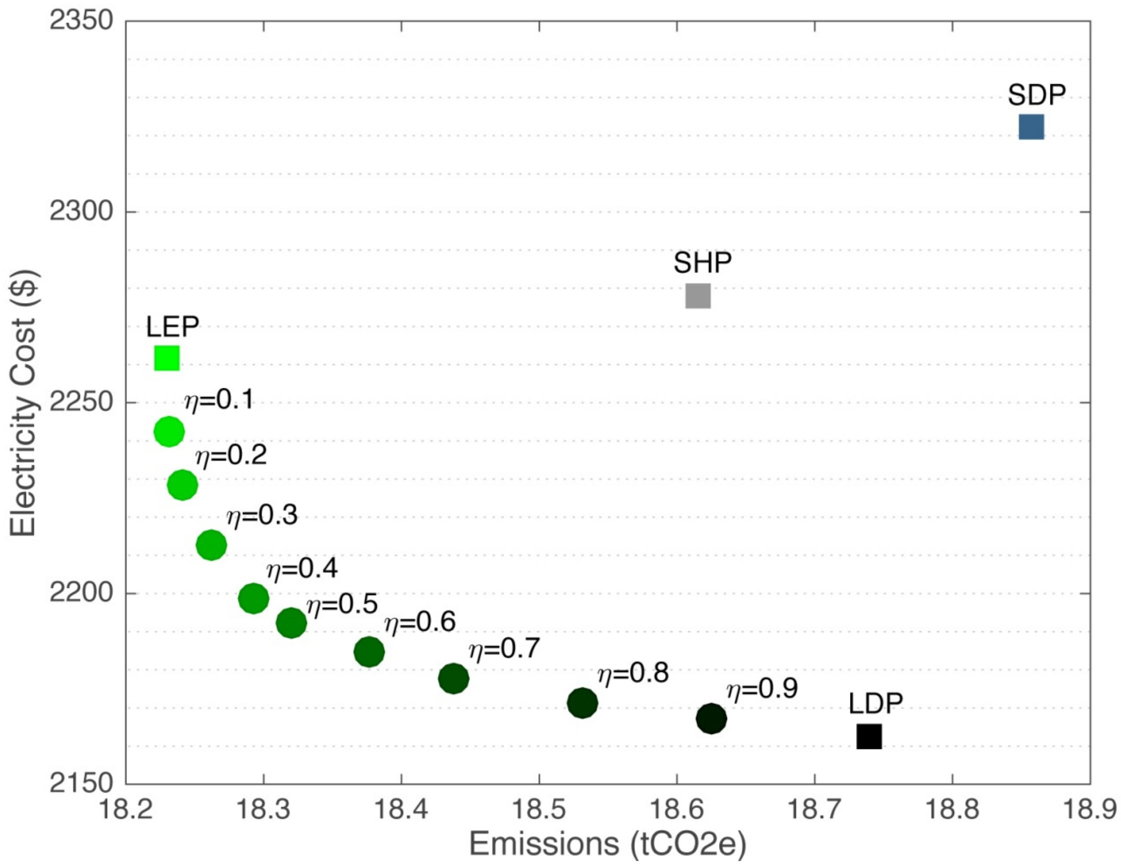
$$BC^r = \sum_{j}^{V} \sum_{w}^{W} WC_j^r . N_j^r \; ; \; \forall r \in R$$

$$WC_j^r = \eta . \frac{\Gamma_j^r}{\Gamma_{Max}^r} + (1-\eta) . \frac{c_j^r}{c_{Max}^r} \; ; \; \forall r \in R, \mathrm{j} \in V$$

Balanced Cost Path



Balanced Cost Path Vs. SDP and SHP



Conclusion

- We consider the reduction of electricity cost and emissions of power markets in a combined manner to address both economic and environmental concerns of ICT.

- Economic and environmental restrictions are two main criteria for any energy consumer. Neither can be improved substantially without impacting the other.

Questions?

Vinod Vokkarane
vinod_vokkarane@uml.edu