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PowerRox™

1st IEEE 5G World Forum

Roadmap Applications & Services Workgroup: 5G is Power Starved

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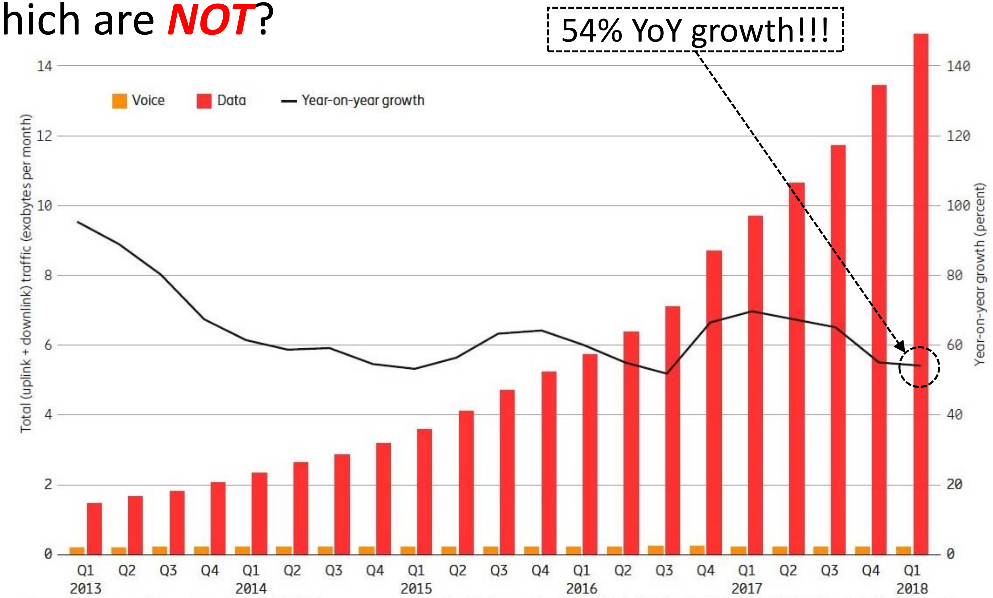
OVERVIEW

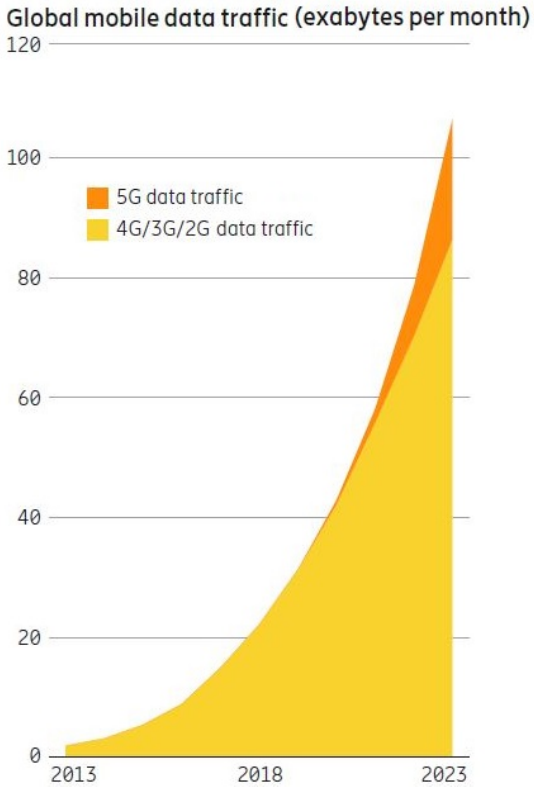
- **Marketing Projections Vs. Reality**
- **What is the power gap?**
- **Power Sources Vs. Loads**
- **Making the Projections a Reality**
- **Summary / Conclusions**

Market Projections Vs. Reality

- **Network Usage Projections**
  - How do these translate to load projections?
  - Which components ***ARE*** Moore's Law Like?
    - Which are ***NOT***?



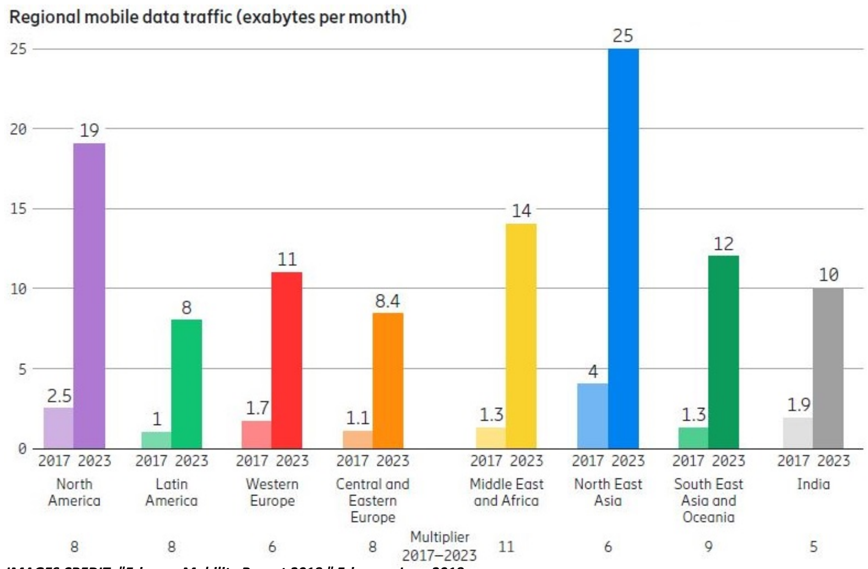
Source: Ericsson traffic measurements (Q1 2018) [1] Traffic does not include DVB-H, Wi-Fi or Mobile WiMAX. VoIP is included in data traffic



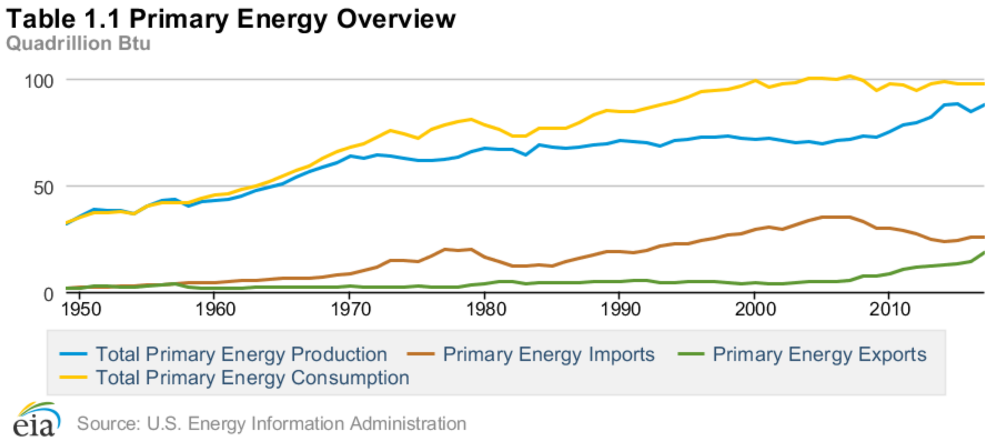
IMAGES CREDIT: "Ericsson Mobility Report 2018," Ericsson, June 2018.

Market Projections Vs. Reality

- **Network Usage Projections**
  - How will shifts in global usage markets impact the availability of power?
  - Is WW power projected to grow on the same trajectory?



IMAGES CREDIT: "Ericsson Mobility Report 2018," Ericsson, June 2018.



IMAGES CREDIT: "Estimated U.S. Energy Net Generation 1950-2018," US EIA, July 2018.

Market Projections Vs. Reality

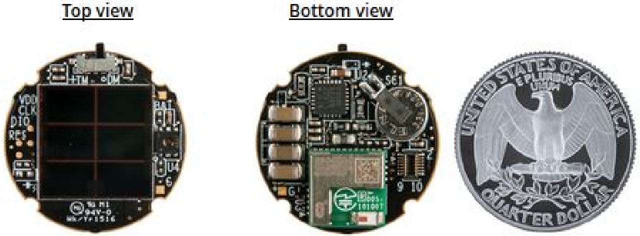


IMAGE CREDIT: CYALKIT-E02 Solar-Powered BLE Sensor Beacon Reference Design Kit (RDK) = http://www.cypress.com/documentation/development-kitsboards/cyalkit-e02-solar-powered-ble-sensor-beacon-reference-design

- **User Usage Projections**
  - How many devices will be out there?
  - What counts as a device?
  - What are these devices depending on for their power source?
  - Are future projections aligned with today's leading-edge or tomorrow's?

IMAGE CREDIT: https://www.phonegg.com/phone/2853-Apple-iPhone-5-GSM-A1428-16GB

IMAGE CREDIT: http://wehavemovedtousa.blogspot.com/2010_10_01_archive.html

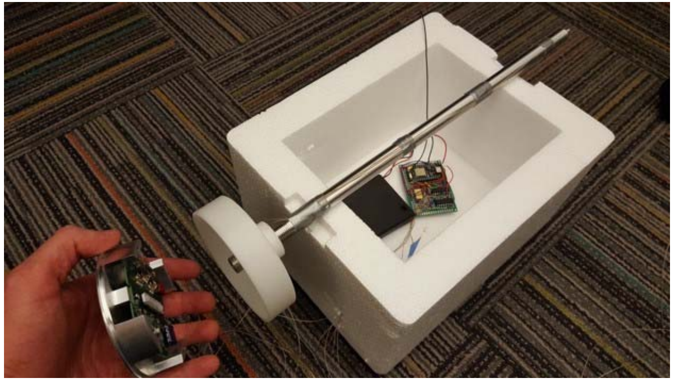
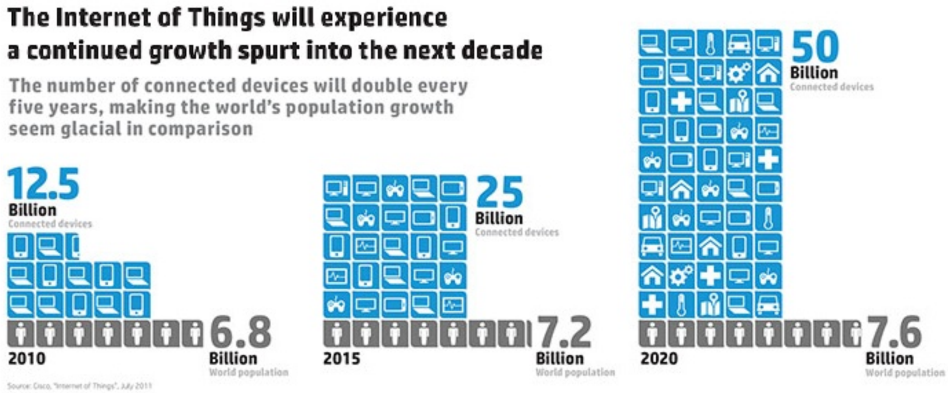
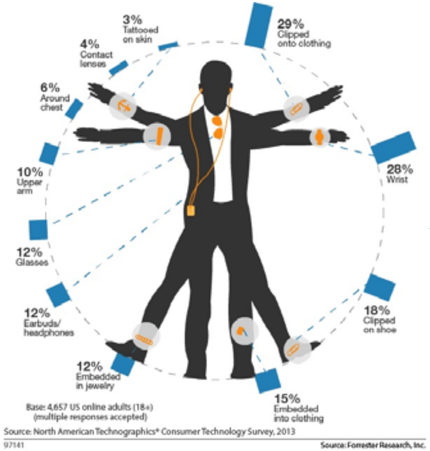


IMAGE CREDIT: M. Dunham, "Chip Scale Thermoelectric Generator for Smart Agriculture," Analog Devices, APEC 2018 Industry Session, San Antonio, TX, March 6, 2018.

Market Projections Vs. Reality

- **What constitutes a device? Or thing? Or mote?**
  - 20-50B IoT Devices, 1T IoT Devices?!?...A **REALLY** Big Number
    - Not getting into IoT semantics here, but most folks agree there will be a whole lot of devices, sensor networks, etc. connected to some form of web/cloud interface.
    - A battery is commonly the limiting factor so the more energy that can be harvested from an ambient source, the more sensor/IoT device applications are enabled. 1T too **LOW** a number???





That is a lot of stuff for a non-bionic being!

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What is the power gap?

- **The Energy Gap**
  - Technology Needs to Catch-up with Projections to Become A Reality

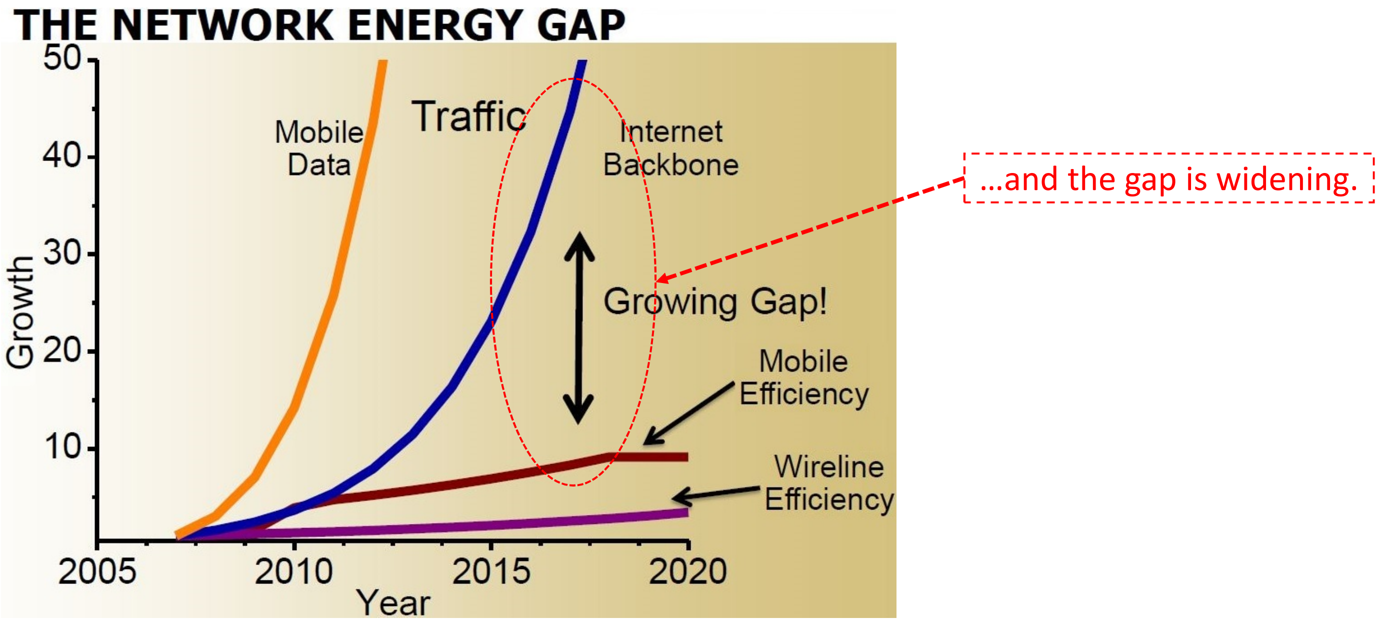
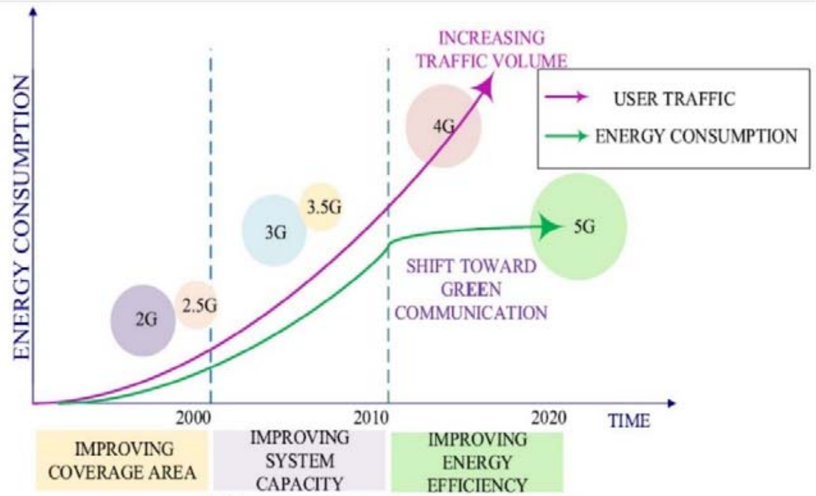


IMAGE CREDIT: Dr. Gee Rittenhouse, "Green Wireless Networks," Alcatel-Lucent GreenTouch, April 2012.

What is the power gap?

- **1000x Traffic**
- **10-1000x Number of Devices**
- **Availability of Power**
- **Sustainability of Power**
- **Impact to Global Power Footprint**
- **Impact to Global Carbon Footprint**



Shift toward green communication.

IMAGE CREDIT: A. Abrol and R. K. Jha, "Power Optimization in 5G Networks: A Step Towards GrEEn Communication," in IEEE Access, vol. 4, pp. 1355-1374, 2016.

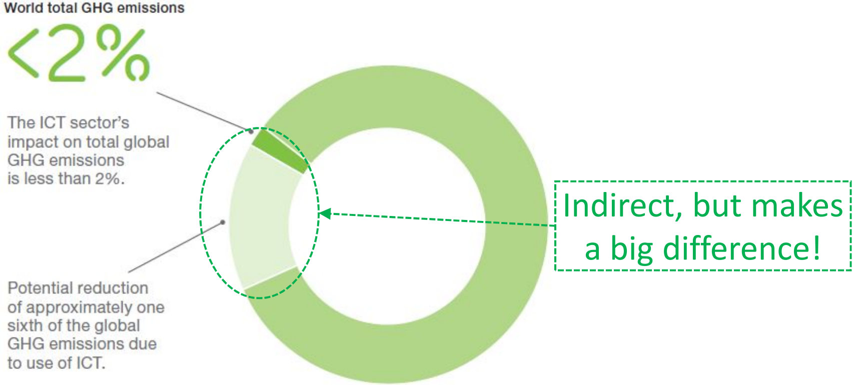


IMAGE CREDIT: "Ericsson Energy and Carbon Report," Ericsson, June 2014.

Power Sources Vs. Loads

- **The Energy Big Picture**

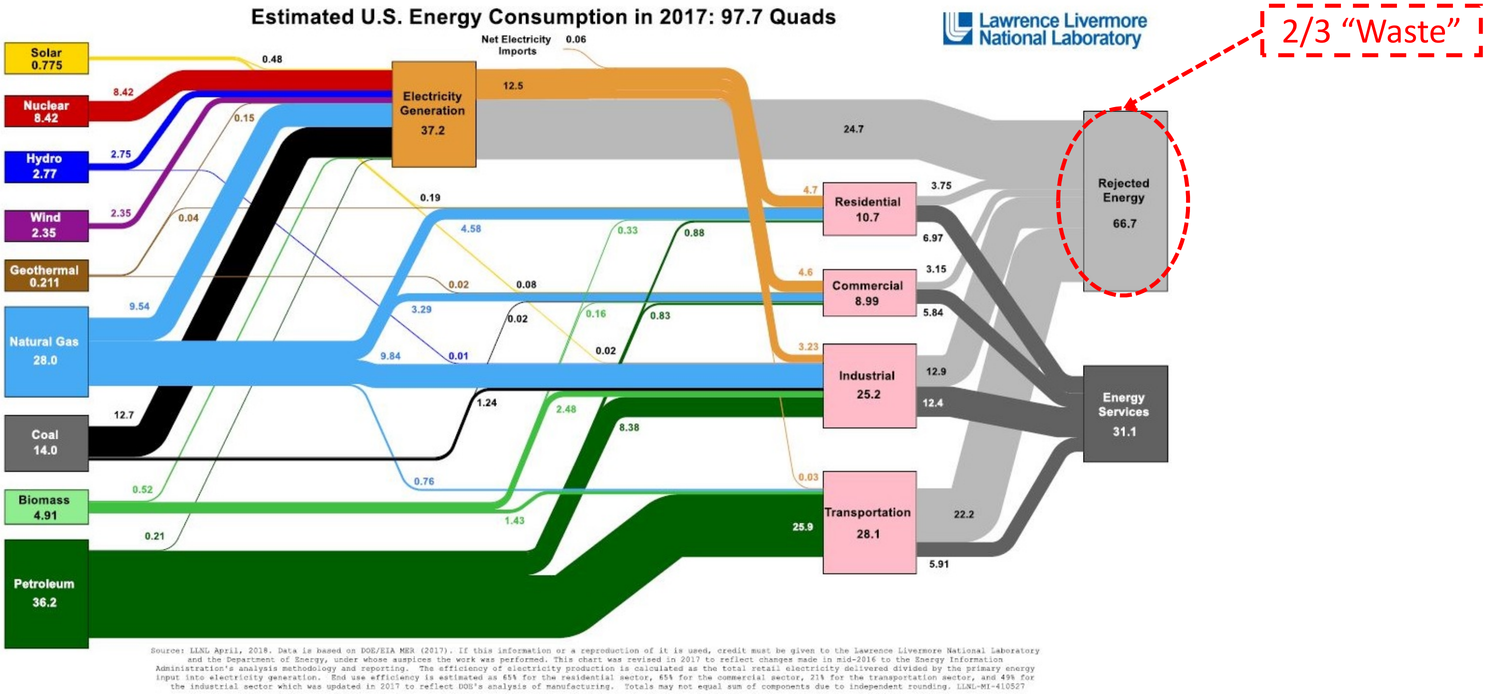
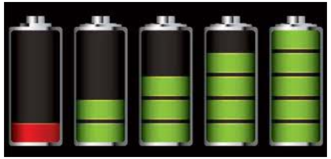


IMAGE CREDIT: "Estimated U.S. Energy Consumption in 2017," Lawrence Livermore National Laboratory, March 2018.

Power Sources Vs. Loads

- **Network Power Sources**
  - Batteries
  - Power Plants
  - Micro/Nanogrids
  - Energy Harvesting
  - Energy Storage



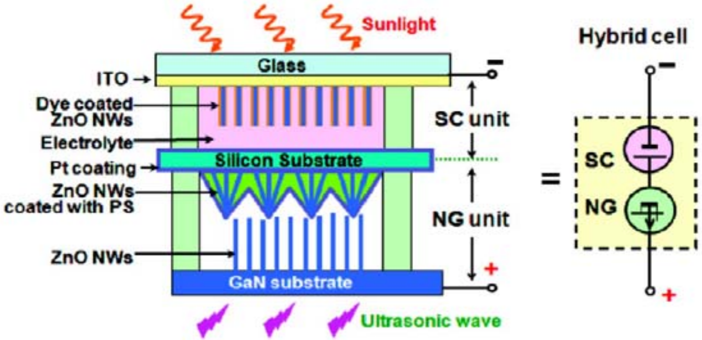


IMAGE CREDIT: Chen Xu, Xudong Wang and Zhong Lin Wang, "Nanowire Structured Hybrid Cell for Concurrently Scavenging Solar and Mechanical Energies", J. Am. Chem. Soc., 131(2009) 5866-5872.

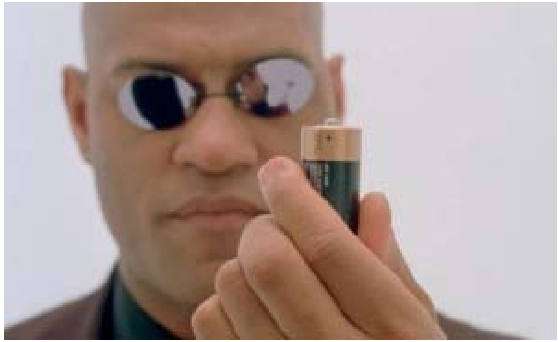


IMAGE CREDIT: Berman, B. (Producer), & The Wachowski Brothers (Director). (1999). The Matrix [Motion Picture]. United States: Warner Bros.

IMAGE CREDIT: Joshua Israelsohn, "Any way the wind blows....," ECN Magazine, July 21, 2014.

IMAGE CREDIT: https://en.wikipedia.org/wiki/Niederaussem_Power_Station

Power Sources Vs. Loads

- **Network Power Sources**
  - US Annual Output
    - 2017 = 97.7 Quads (~16.6% of WW Output)
  - WW Annual Output
    - 2017 = 589 Quads **[baseline]**
    - 2020 *(projected)* = 605 Quads **[+2.7%]**
    - 2030 *(projected)* = 663 Quads **[+12.6%]**
  - Telco Total Consumption = <1% WW
    - Data Center Consumption = ~20% WW

Quad = quadrillion BTUs
= ~293 TWh

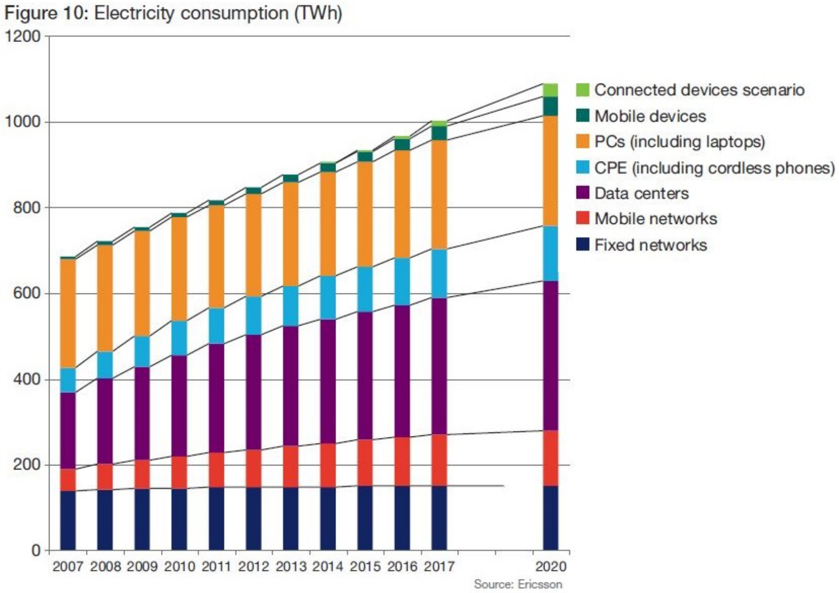


IMAGE CREDIT: "Ericsson Energy and Carbon Report," Ericsson, June 2013.

Power Sources Vs. Loads

- **Network Power Loads**
  - Base Stations
  - IT Equipment
  - UEs

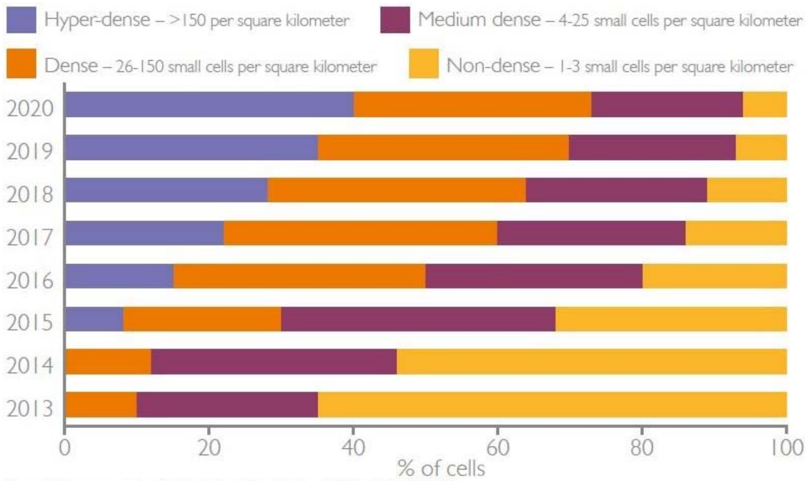


Figure 3. Percentage of small cells deployed in various levels of density 2013-2020

IMAGE CREDIT: "Crossing the Chasm: Small Cells Industry November 2015," Smart Cell Forum, November 2015.

IMAGE CREDIT: http://uiconstock.com/wp-content/uploads/2015/11/Free-Billboard-Mockup.jpg

IMAGE CREDIT: James Cameron (Producer), & James Cameron (Director). (1991). Terminator 2: Judgment Day [Motion Picture]. United States: Carolco Pictures

IMAGE CREDIT: CDMA spectral efficiency - Wikipedia, 2016. [Online]. Available: https://en.wikipedia.org/wiki/CDMA_spectral_efficiency.

IMAGES CREDIT: http://tricorder.xprize.org/

IMAGE CREDIT: https://www.flickr.com/photos/ubiquisys/5428267528/

Power Sources Vs. Loads

- **Network Power Loads**
  - Napkin Calcs
    - (1) Smartphone = ~10 Wh/day = 3.65 kWh/year
      - (3B) Smartphones = ~11 TW/year
      - (6B) Smartphones = ~22 TW/year
    - (1) IoT Device = ~10 mWh/day = 3.65 Wh/year
      - (30B) Devices = ~0.11 TW/year
      - (50B) Devices = ~0.18 TW/year
      - (1T) Devices = ~3.7 TW/year
    - RF Transceiving
      - Tx power = 2-4 orders of magnitude larger than Rx power
      - Base Stations = 10-1000W, 40-60% overall efficiencies
    - Utility Distribution
      - 5-15% loss in getting power from generation to load

Making the Projections a Reality

- **Base Stations**
  - Biggest Chunk of the Pie

Holy smokes!!!
(and this info is even a little dated)

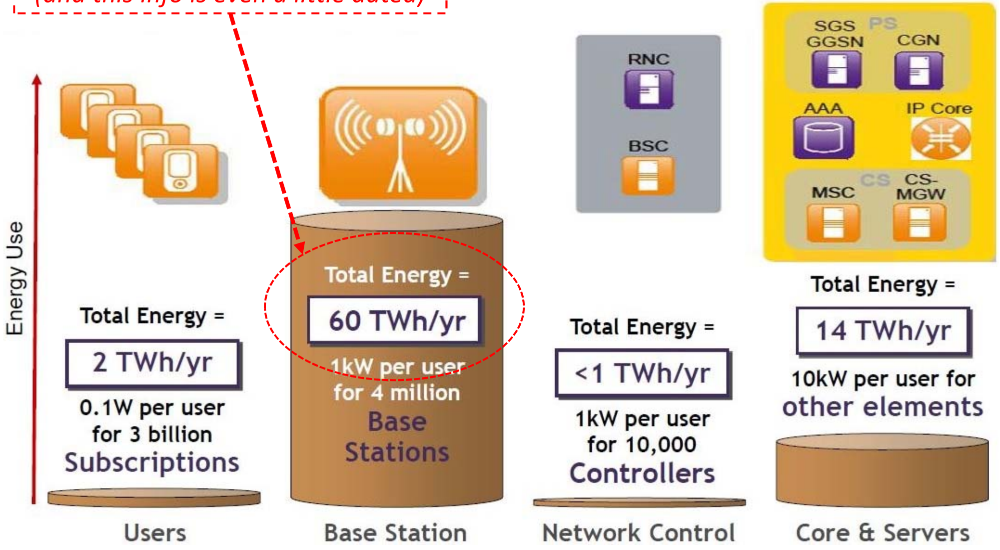


IMAGE CREDIT: Dr. Gee Rittenhouse, "Green Wireless Networks," Alcatel-Lucent GreenTouch, April 2012.

Take note of the major differences here.

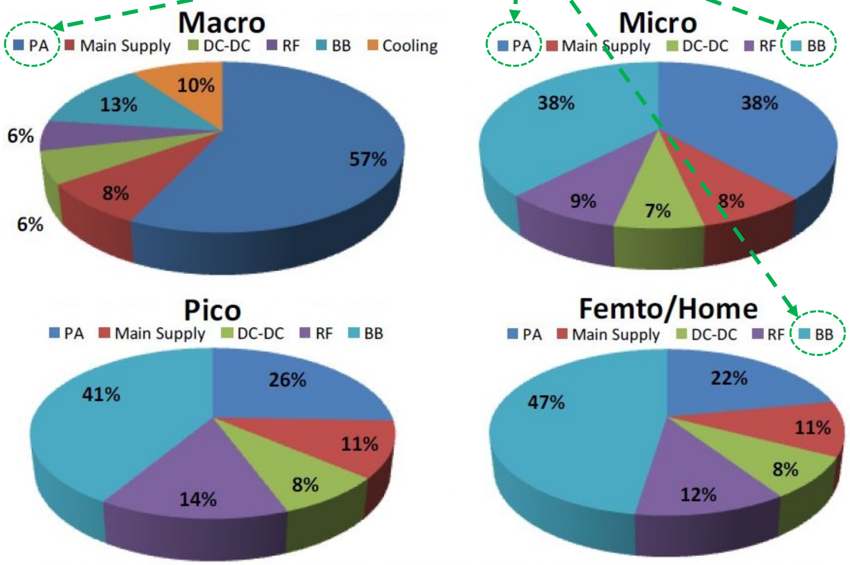


FIGURE 12. BS power consumption breakdown for different deployment scenarios.

IMAGE CREDIT: "Energy efficiency analysis of the reference systems, areas of improvements and target breakdown," EARTH, Deliverable D2.3 v2.00, January 31, 2012.

Making the Projections a Reality

- **Intelligent Power Management (IPM)**
  - Applies to Entire Network
  - More Adaptable to Real-Time Power Markets
- **Dynamic Base Station Power**
  - Smaller Power = More Dynamic
  - React to Real-Time Traffic, Not Statistical Traffic Patterns
  - Analog-to-Digital (ADC): Number of Bits Vs. Sampling Rate
- **Radio Frequency (RF) Power Amplifier (PA) Optimization**
  - mm-wave / Massive Multi-Input Multi-Output (mMIMO)
  - Envelope Tracking

Making the Projections a Reality

- **Base Stations**
  - Biggest Opportunities for Improvement
    - PA Biggest Chunk of the Biggest Chunk

Table 2. Proposed techniques for improving PA efficiency.

Techniques		Enhancements	Limitations
Digital pre-distorted Doherty-architectures and GaN [24]		Up to 50%	Requires extra feedback for pre-distortion and signal processing.
Envelope tracking designs [39]		Up to 60%	Requires a very fast and high-bandwidth power supply as well as an accurate envelope signal for power supply.
Switched mode PA (SMPA) [35]	Class-AB	60%–70%	Overlap between voltage and current, which reduces efficiency.
	Class-D	70%	High peak voltage and limited operation between 1 GHz and 2 GHz.
	Class-F	75%	Realizing harmonic terminations at high frequencies presents a main challenge. Practical designs are typically limited to terminating the third harmonic.
	Class-E	85%	Can be supported by a transistor with slow switching characteristics and is better suited to high-frequency operations.

IMAGE CREDIT: Alsharif, M.H., Kim, J., Kim, J.H., "Green and Sustainable Cellular Base Stations: An Overview and Future Research Directions," Energies 2017, 10, 587.

Making the Projections a Reality

- **Lots of Hops, Lots of Opportunities for Consolidation**

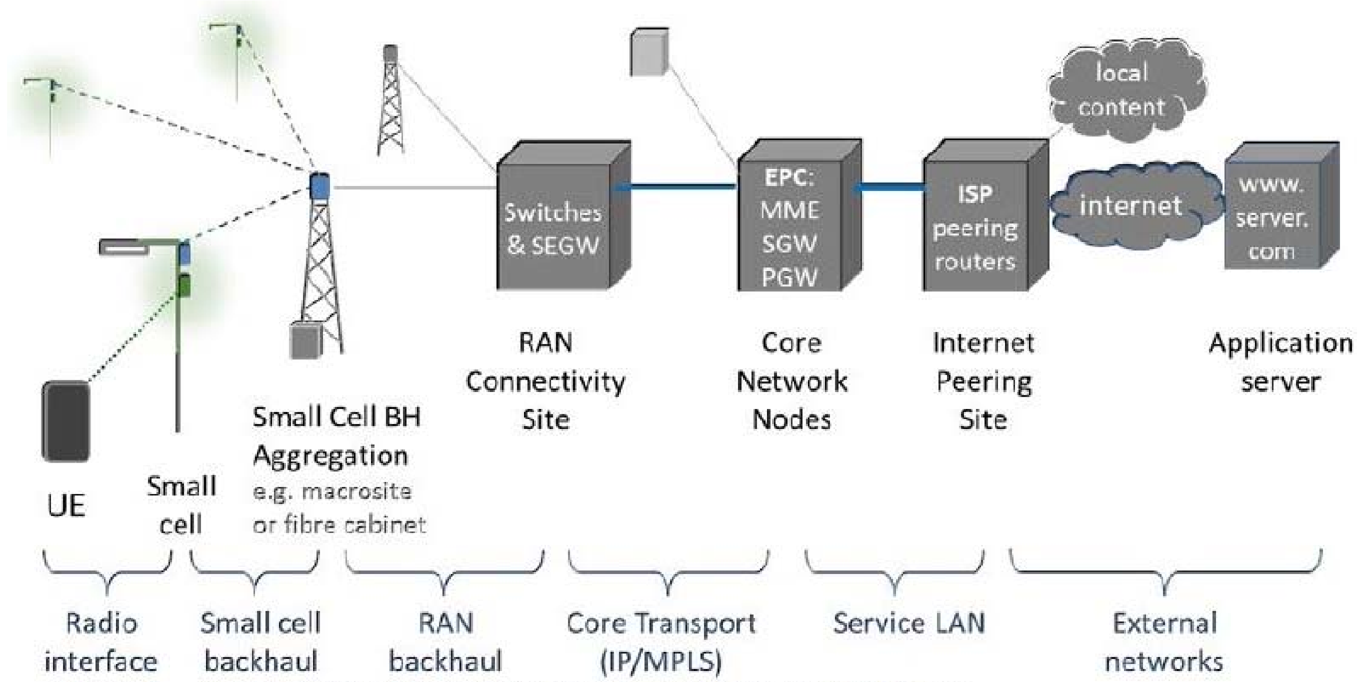


Figure 4-4 **Segments in the end-to-end connection between the user terminal and the application server in the internet (a macrocell aggregation is assumed)**

IMAGE CREDIT: "Backhaul technologies for small cells: Use cases, requirements and solutions," Smart Cell Forum, February 2013.

Making the Projections a Reality

- **Network-Level Efficiency Improvements**
  - GreenTouch Consortium Green Meter Research Study
    - *"The study concluded that it is possible through the combination of technologies, architectures, components, algorithms and protocols to reduce the net energy consumption in end-to-end communications networks by up to **98%** by 2020 compared to the 2010 reference scenario defined by GreenTouch."*
      - *"**10,000-fold** increase of energy efficiency in mobile access networks"*
      - *"**254-fold** increase in energy efficiency in residential fixed access networks"*
      - *"**316-fold** increase in energy efficiency in core networks"*

	Energy Efficiency Improvement Factor (2020 vs. 2010 Reference Scenario)	Traffic Growth (from 2010 to 2020)	Net Energy Reduction of 2020 Relative to 2010
Mobile Access	10,000x	89x	99%
Fixed Access (Residential)	254x	8x	97%
Core Network	316x	12x	96%

Table 7: Summary of the Green Meter Research study with the energy efficiency gains, traffic growth and net energy reductions that can be achieved in the mobile access, fixed access and core networks.

IMAGE CREDIT: "GreenTouch Final Results from Green Meter Research Study," A GreenTouch White Paper, Version 2.0, August 15, 2015.

Making the Projections a Reality

- **Network-Level Efficiency Improvements**
  - GreenTouch Consortium Green Meter Research Study
    - Network Equipment Power Reductions

GreenTouch™

Device	Power Consumption in 2010	Power Consumption in 2020
Router Port 40 Gb/s	825 W	21.3 W
Router Port 100 Gb/s	Not widely deployed	39.2 W
Router Port 400 Gb/s	Not widely deployed	46.7 W
Router Port 1000 Gb/s	Not widely deployed	53.9 W
Transponder 40 Gb/s	167 W, reach 2500 km	27.6 W, reach 2500 km
Transponder 100 Gb/s	Not widely deployed	86 W, reach 1200 km
Transponder 400 Gb/s	Not widely deployed	332.6 W, reach 400 km
Transponder 1000 Gb/s	Not widely deployed	801.3 W, reach 350 km
Regenerator 40 Gb/s	334 W, reach 2500 km	55.2 W, reach 2500 km
Regenerator 100 Gb/s	Not widely deployed	172 W, reach 1200 km
Regenerator 400 Gb/s	Not widely deployed	665 W, reach 400 km
Regenerator 1000 Gb/s	Not widely deployed	1602.6 W, reach 350 km
EDFA	55 W	15.3 W
Optical Switch	85 W	8.5 W

Table 5: Power consumption and reach of network components in 2010 and 2020 networks

IMAGE CREDIT: "GreenTouch Final Results from Green Meter Research Study," A GreenTouch White Paper, Version 2.0, August 15, 2015.

Making the Projections a Reality

- **Network-Level Efficiency Improvements**
  - GreenTouch Consortium Green Meter Research Study
    - Network Equipment Power Reductions

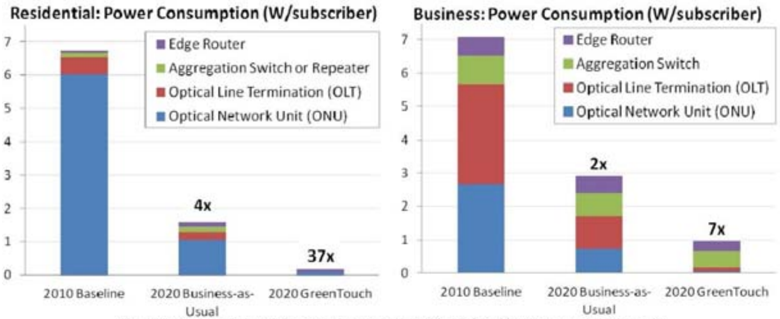


Figure 7: Power consumption improvement in residential and business access networks

IMAGE CREDIT: "GreenTouch Final Results from Green Meter Research Study," A GreenTouch White Paper, Version 2.0, August 15, 2015.

	Residential Fixed Access		Business Fixed Access	
	2010 Baseline	2020 GreenTouch	2010 Baseline	2020 GreenTouch
Energy Efficiency	20.5 kb/J	5200 kb/J	77 kb/J	2343 kb/J
Energy Efficiency Improvement Factor relative to 2010		254x		30x
Energy Consumption per Year for all Group 1 Subscribers	14.47 TWh	0.45 TWh	941 GWh	171 GWh
% Energy Savings per Year versus 2010		97%		82%
Analogies - Annual GHG emissions from Cars		2,035,000		112,000

Table 4: Energy consumption and energy efficiency in residential and business access networks

IMAGE CREDIT: "GreenTouch Final Results from Green Meter Research Study," A GreenTouch White Paper, Version 2.0, August 15, 2015.

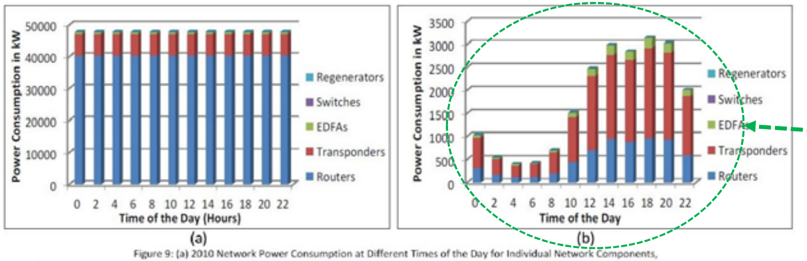


Figure 9: (a) 2010 Network Power Consumption at Different Times of the Day for Individual Network Components, (b) 2020 Network Power Consumption at Different Times of the Day for Individual Network Components with GreenTouch Initiatives Implemented

Power optimization adapted for known load behaviors.

IMAGES CREDIT: "GreenTouch Final Results from Green Meter Research Study," A GreenTouch White Paper, Version 2.0, August 15, 2015.

Making the Projections a Reality

- **Network-Level Efficiency Improvements**
  - GreenTouch Consortium Green Meter Research Study
    - Network Equipment Power Reductions
      - Quantifying the Possibilities

	Technology	Improvement Factor
1	Improvement in Components due to Moore's Law	4.23x
2	GreenTouch Equipment Innovations	4.73x
3	Intelligent Energy Aware Protection	1.96x
4	Optical Bypass and Low Energy State Modes	2.13x
5	Mixed Line Rates	1.21x
6	Physical Topology Optimization	1.43x
7	Distributed Clouds for Content Distribution and Network Equipment Virtualization	2.19x
	Total Improvement in 2020 due to GreenTouch Initiatives	**316x**

Table 6: Energy efficiency gain factors for various GreenTouch techniques in core networks

	Energy Efficiency Improvement Factor (2020 vs. 2010 Reference Scenario)	Traffic Growth (from 2010 to 2020)	Net Energy Reduction of 2020 Relative to 2010
Mobile Access	10,000x	89x	99%
Fixed Access (Residential)	254x	8x	97%
Core Network	316x	12x	96%

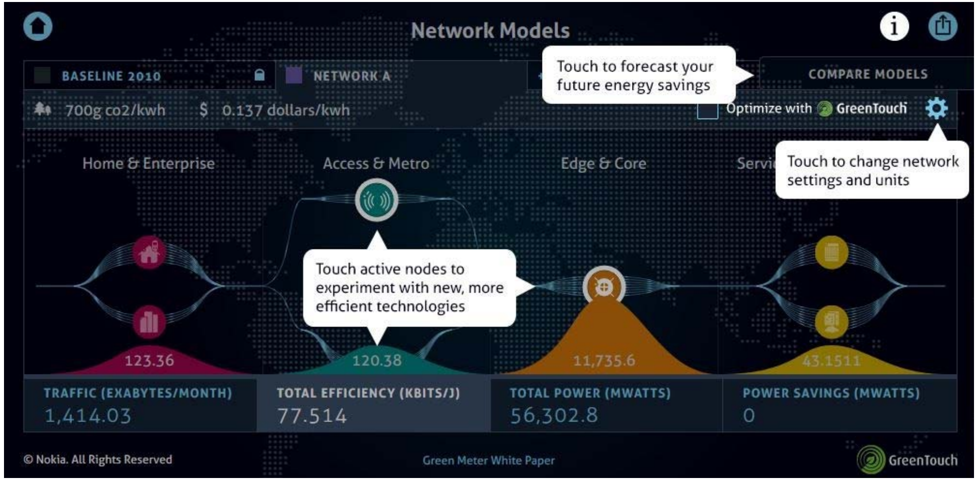
Table 7: Summary of the Green Meter Research study with the energy efficiency gains, traffic growth and net energy reductions that can be achieved in the mobile access, fixed access and core networks.

Wow, amazing improvement opportunities, ***even with*** dramatic traffic growth predictions!!!

IMAGES CREDIT: "GreenTouch Final Results from Green Meter Research Study," A GreenTouch White Paper, Version 2.0, August 15, 2015.

Making the Projections a Reality

- **Network-Level Efficiency Improvements**
  - GreenTouch Consortium Green Meter Research Study
    - Resources/Tools
      - Tons of Overview Materials = http://greentouch.org
        - Green Meter White Paper
      - GWATT Calculator (Network-Level Simulation) = http://alu-greentouch-dev.appspot.com/



IMAGES CREDIT: "GWATT - Visualizing the GreenTouch Results," GreenTouch Celebration, GreenTouch Foundation, June 18, 2015.

Making the Projections a Reality

- **Network-Level Efficiency Improvements**
  - GreenTouch Consortium Green Meter Research Study
    - Resources/Tools
      - ➢ IMEC Base Station (BS) Simulator/Calculator = https://www.imec-int.com/powermodel

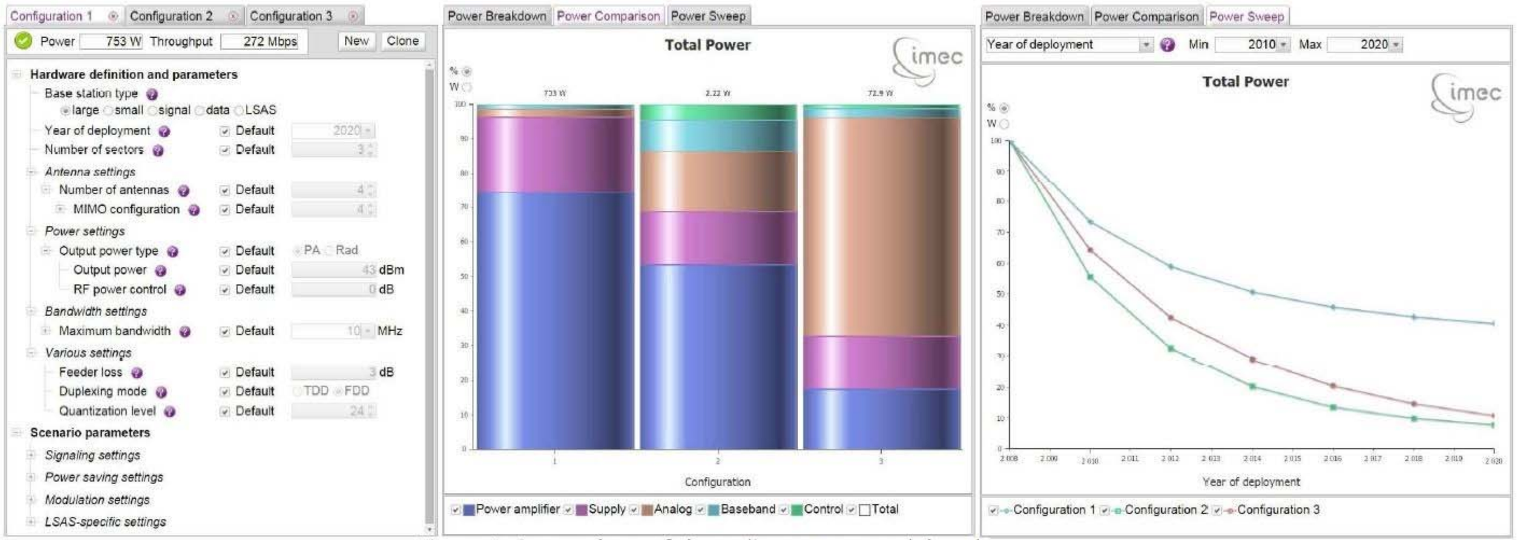


Figure 4: Screenshots of the online power model tool

IMAGE CREDIT: "GreenTouch Final Results from Green Meter Research Study," A GreenTouch White Paper, Version 2.0, GreenTouch Foundation, August 15, 2015.

Making the Projections a Reality

- **Network-Level Efficiency Improvements**
  - Other Industry Efforts / Consortiums
    - EARTH
    - OPERA (GreenTouch)
    - Major Industry Partners

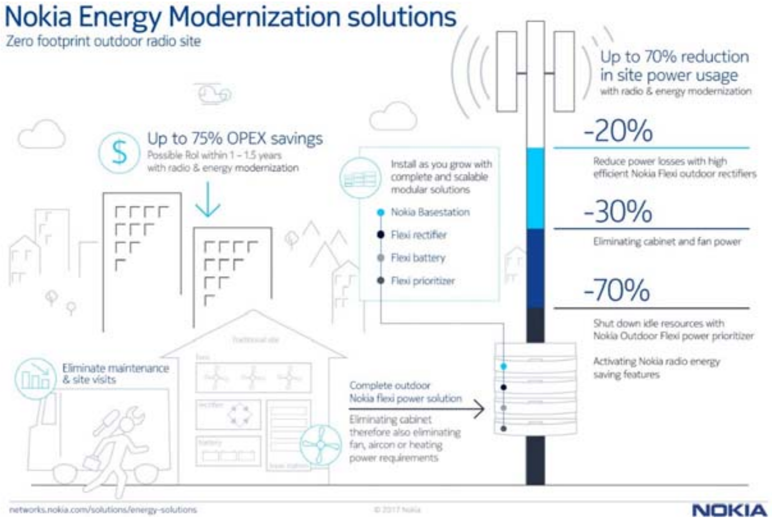


IMAGE CREDIT: Nokia AirScale Solution = https://networks.nokia.com/solutions/energy-solutions

earth
Energy Aware Radio and neTwork tecHnologies

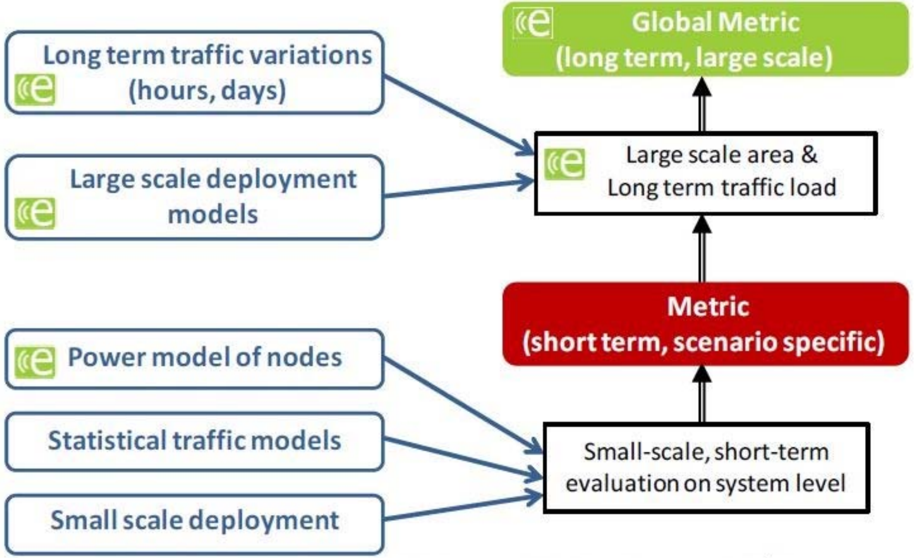
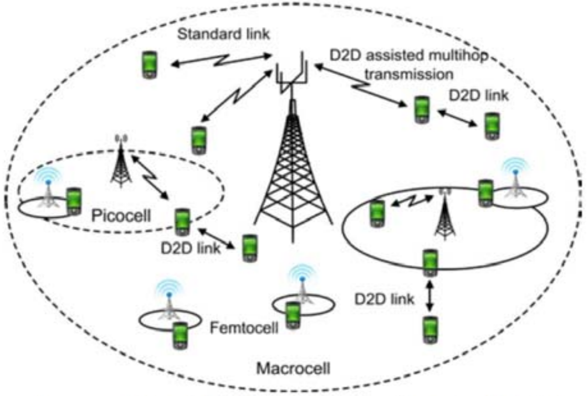


FIGURE 1. Global energy efficiency evaluation framework (E^3F)

IMAGE CREDIT: "Energy efficiency analysis of the reference systems, areas of improvements and target breakdown," EARTH, Deliverable D2.3 v2.00, January 31, 2012.

Making the Projections a Reality

- **Device-to-Device (D2D) Communications**
  - Analogous to Mesh Networks
  - Mitigate the Transmission
- **Peak Shaving**
  - Size Infrastructure for the Average, Not the Peak
  - Localized Energy Storage
- **Edge Buffering**
  - Mitigate the Transmission
  - Leverage & Re-use



An example of D2D communications in HetNets.

IMAGE CREDIT: Z. Bojkovic, M. Bakmaz, B. Bakmaz, "On the Road to Energy Efficient 5G Mobile Networks" Recent Advances on Systems, Signals, Control, Communications and Computers, pp. 137-140, 2015.

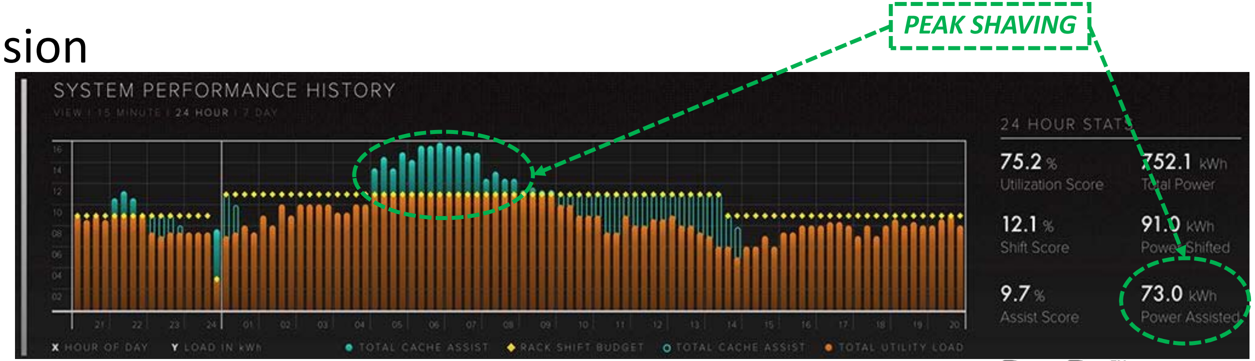


IMAGE CREDIT: Virtual Power Systems VPS ICE Console Screen Shot. http://www.virtualpowersystems.com/our-platform.

Making the Projections a Reality

- **Simultaneous Wireless Information & Power Transfer (SWIPT)**
  - Optimize Intelligence for Data & Power Simultaneously
- **Relays**
  - Save Power, Be Secure, & Scavenge Energy Simultaneously
- **Energy Harvesting**
  - Scavenge Energy from All Physical Sources
  - Supplement Battery Life
  - Energy Independence = Security
  - Low Power = Security
- **Software-Defined / Virtualized Everything (SD*x* / V*x*)**

Making the Projections a Reality

- **Energy Harvesting**
  - Utilizing every μW available.

*"There is no such thing as **waste heat**…just underutilized **energy recycling opportunities**."*

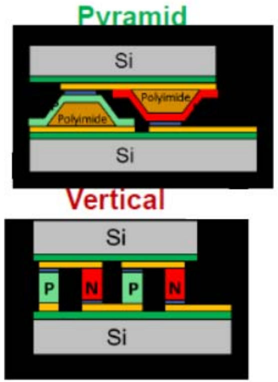
– Brian Zahnstecher

IMAGE CREDIT: D. Hess, "Truly Transparent Power," IDTechEx US Show, Santa Clara, CA, Nov 17, 2016.

IMAGES CREDIT: V. Micelli, "Pavegen - The Future of Urban Energy," IDTechEx US Show, Santa Clara, CA, Nov 17, 2016.

Making the Projections a Reality

- **Energy Harvesting**
  - Even IC-level



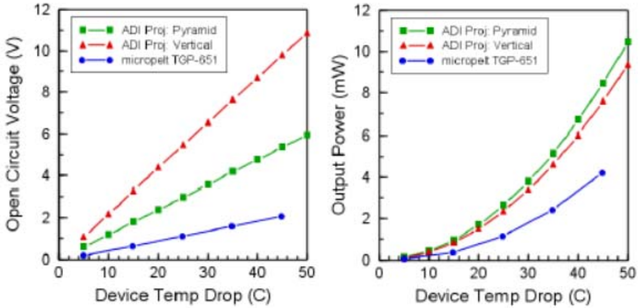
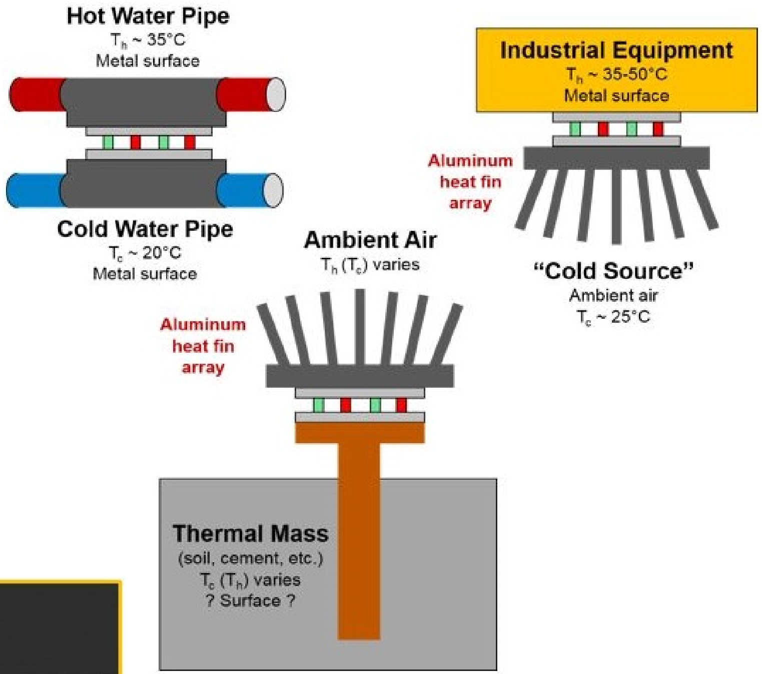
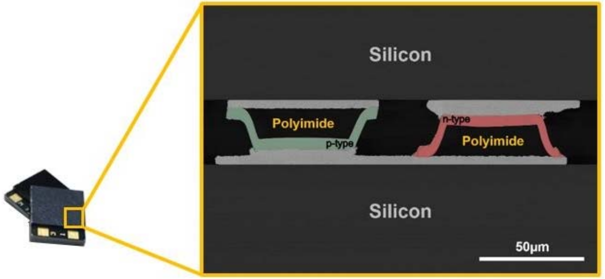


IMAGE CREDIT: B. Chen, J. Cornett, "Chip Scale TEG and its Use for a Wireless Machine Health Monitoring System," Analog Devices, APEC 2017 Industry Session, Tampa, FL, March 30, 2017.





IMAGES CREDIT: M. Dunham, "Chip Scale Thermoelectric Generator for Smart Agriculture," Analog Devices, APEC 2018 Industry Session, San Antonio, TX, March 6, 2018.

Summary / Conclusions

- **All the awesome applications enabled by the many enhanced specs and features of the 5G network provide many power challenges as well as opportunities.**
- **There exists a large gap between projections of energy utilization and how energy is produced/utilized for things on the 5G network.**
  - If you are talking dramatic growth of edge power representing only ~1% of WW energy pie today, has much greater overall impact to global power needs.
- **The biggest consumer of network power is also the biggest opportunity for power savings.**
- **Many of needs have been identified, data collected, tools provided.**
- **Energy harvesting can play a big role in all aspects of the network.**

Q & A

IEEE 5G World Forum

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Thanks a lot for your time and attention!

Any questions and/or comments?

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