




High Temperature Superconductors (HTS) as Enabling Technology for Sustainable Mobility and Energy Efficiency

2PL1A-01 ASC 2018, Seattle, WA, USA
CT REE ELM – Dr. Tabea Arndt – 30.Oct.2018

Unrestricted © Siemens AG 2018

Siemens Corporate Technology


The Trident



Major concerns of Electrical Engineers NOT deeply in the field of superconductivity

The three issues of the trident

- **Cost**
 - material processing
 - system view, communication of benefits
- **Higher T_c**
 - material scientists
 - education that T_c is not the most important property of SCs
- **Cooling requirements**
 - conventional equipment requires heat removal, too
 - less effort than expected



Unrestricted © Siemens AG 2018
Page 2 20181030 – Tabea Arndt Corporate Technology

This is NOT a Halloween tool!

When approaching engineers in established power technology, then three perceived basic issues appear usually.

- **COST:** superconducting technology appears to be expensive


The cost issue is to be approached by improving the specific performance (e.g. by decreasing the \$/kAm for specific applications) and –when the market is developing- by economy of scale.

- **T_c:** would be good to have a higher T_c, or even better a room temperature superconductor
- **Cooling:** there is the need for sophisticated and extensive cooling to use superconductors

But first, conventional equipment needs cooling/ heat removal, too. For many copper-based devices, there is more IP in heat removal than in electromagnetic design!

Second, cryogenic cooling according to the state of the art is less effort than usually expected, and ,due to the small amount of heat to be removed, is still beneficial.

Contents



Contents

- Introduction
- Energy Technology
- Mobility
- Conclusions

Unrestricted © Siemens AG 2018
Page 3 20181030 – Tabea Arndt Corporate Technology

In this contribution, after a short introduction (partly already done) we will address some devices in power engineering, then discuss the application and general aspects in mobility, and finally conclude.

T_c

SIEMENS
Ingenuity for Life

Critical current I_c in self field for 1G- and 2G-HTS tapes

T_c matters, but is not a key property

From I_c -considerations in self field:

- Bi-2223 seems well suited for applications of low magnetic field and high operating temperature.
- RE-123 is more beneficial for operating temperatures below abt. 80 K

$I_c(T, \text{ self field})$ of HTS (4 mm wide)

Temperature T [K]	I_c [A] (Bi-2223)	I_c [A] (RE-123)
20	2100	-
40	1400	-
50	1000	500
60	700	400
80	300	200
90	0	100
100	-	50
110	-	0

Principal sketch of critical current according to presently available datasheets.

Unrestricted © Siemens AG 2018
Page 4 20181030 – Tabea Arndt Corporate Technology

Considering the “issue T_c ” from the trident, one might answer referring to the two most important technical HTS wires.

T_c matters (we will see that when discussing the cooling issue, too), but is not the most crucial property.

In self field (magnetic), the “lower T_c HTS” RE-123 shows a higher critical current I_c than the “higher T_c HTS” Bi-2223 for temperatures below about 80 K.

Considering a magnetic field of e.g. 1 T the situation becomes even more pronounced (see next slide).

T_c

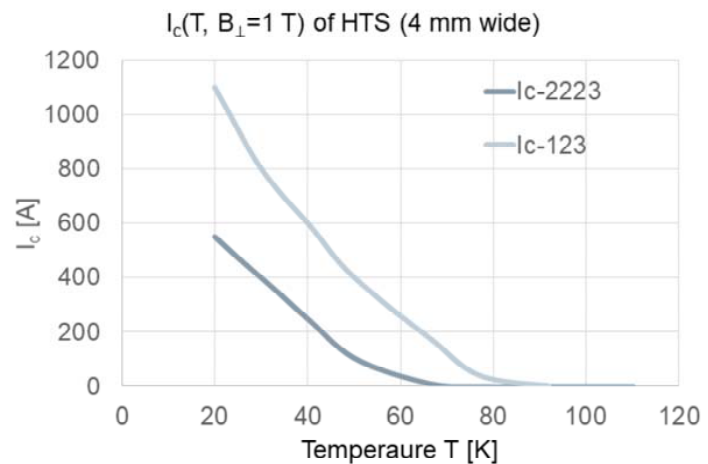
SIEMENS
Ingenuity for life

Critical current I_c in $B_{\perp}=1$ T for 1G- and 2G-HTS tapes

T_c matters, but is not a key property

From I_c -considerations in $B_{\perp}=1$ T :

- Seems to be more beneficial to use RE-123 tapes.



Principal sketch of critical current according to presently available datasheets.

Unrestricted © Siemens AG 2018

Page 5

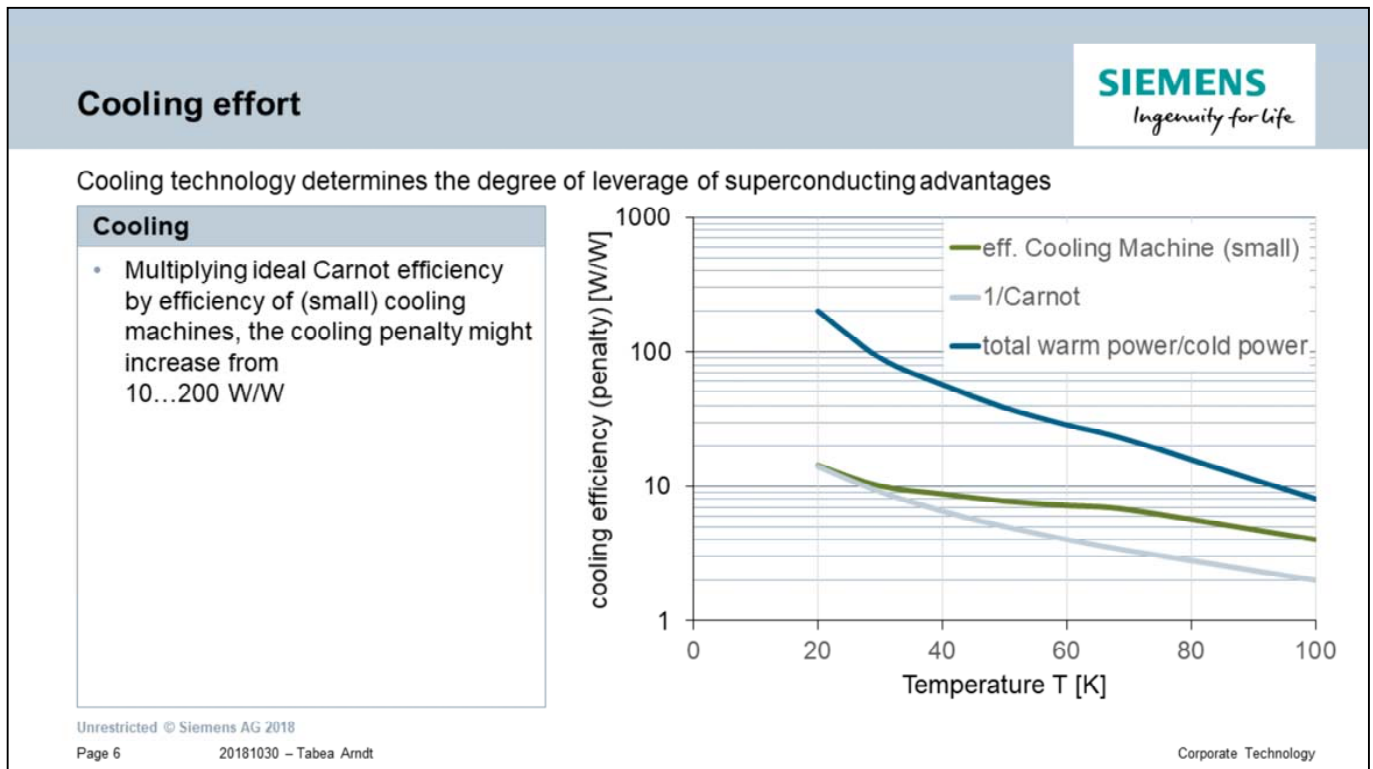
20181030 – Tabea Arndt

Corporate Technology

In a magnetic field of $B=1$ T, the “lower T_c HTS” RE-123 shows a higher critical current I_c than the “higher T_c HTS” Bi-2223 for all temperatures below 90 K.

There is a beneficial window of opportunity for Bi-2223 for high temperatures (e.g. $T>90$ K) and small magnetic fields (as in e.g. power lines/ cables).

Let's consider the cooling issue (remember trident) (see next slide).

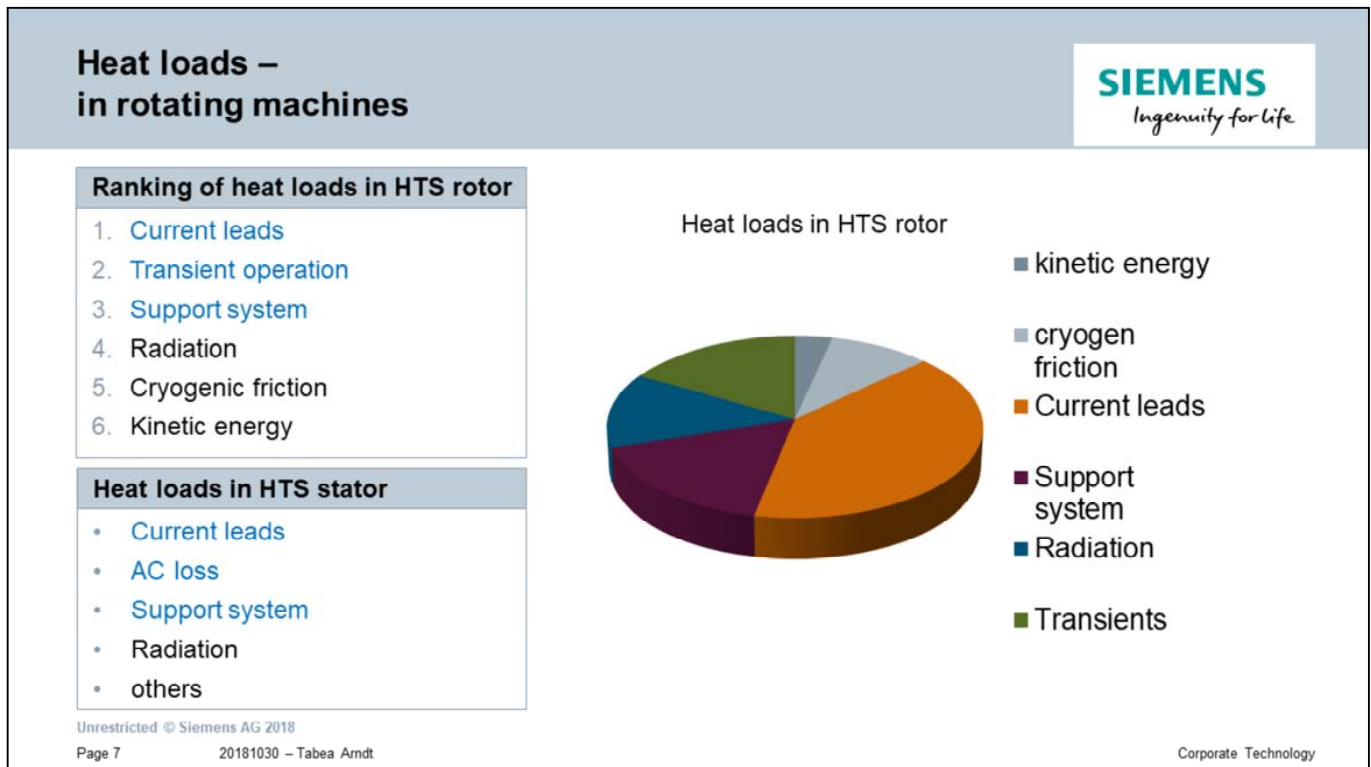


(The graph is typical taken from the range of different small cooling machines; green curve)

The total cooling effort in terms of power needed at room temperature to remove a certain loss at lower temperature is the product of the ideal Carnot efficiency and the efficiency of the cryo cooler (here only small cooling machines are considered; large cooling machines e.g. in air separation units have a much larger efficiency).

From that, we see that the cooling penalty (a “tax” on the heat “expenditures” of the device) ranges from 10...200 W/W depending on the operating temperature.

What kind of heat loads at low (operating) temperature are to be considered? (See next slide)



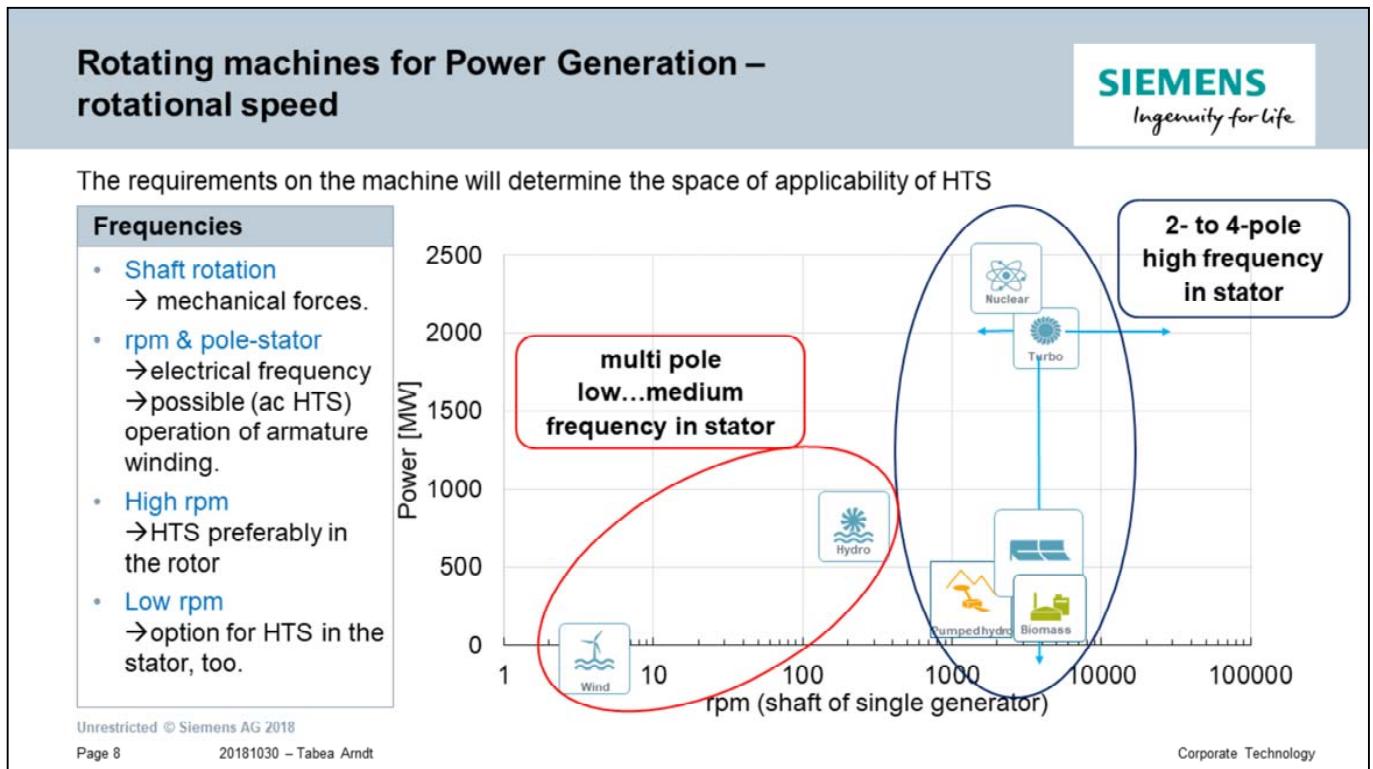
As an example, we might refer to the heat loads in a rotating machine.

The “heat pie” shows the contribution of some source for a HTS rotor.

The most prominent heat load might origin from the current leads, followed by loss due to transient operation (e.g. change in excitation and corresponding ac-loss) and by the mechanical support system (environmental heat conduct).

When applying HTS technology in a stator, the situation is similar, but there is no ranking due to strong dependence on actual machine and design.

Different machines and designs might be considered in two clusters (see next slide).



The clusters may be characterized by the rotational speed of the shaft of the machine.

The mechanical rotation determines the centrifugal forces to be covered by the support system and together with the pole configuration determine the electrical frequency.

If the electrical frequency is not too high, there will be the option to use (ac-loss optimized) HTS in the armature winding, too.

If the electrical frequency is very high (e.g. turbo machines), then –at least presently- the HTS should be used in the rotor in a quasi-DC mode only.

Let's first consider the turbo machines cluster (see next slide).

Generators - Turbo-Generators



Turbo generators show clear benefit in energy efficiency when applying HTS in the rotor (only)

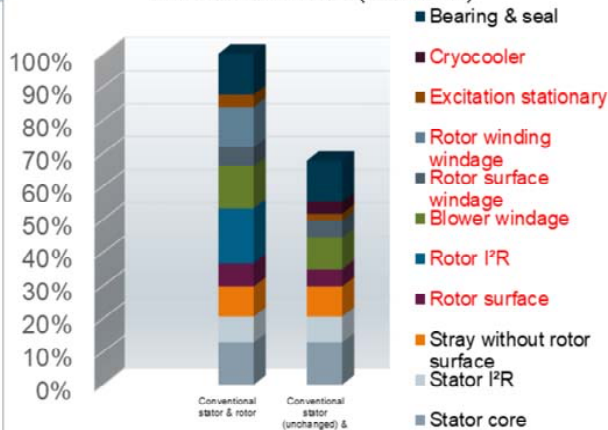
Losses reduced

Cu I²R-loss: -500 kW
 T_{op}=30 K: x80 W/W
 max. allowed loss:
 500 kW/80= 6.3 kW

Very high value for superconductors, a lot of freedom to design

→ Very high justification by efficiency!

Loss at rated load (250 MVA)



Several 100 MW power plant



New York City: Co-Op City ordered 40 MW power plant

Unrestricted © Siemens AG 2018

Page 9

20181030 – Tabea Arndt

Corporate Technology

Let's consider a 250 MVA power plant generator (e.g. right top picture; the right bottom picture shows a small residential power plant in New York City).

All loss components highlighted in red in the graph will be changed by using HTS technology in the rotor.

The Cryocooler-share is newly introduced, but all other red marked loss shares are reduced considerably.

A conventional, Copper-based generator would have an ohmic loss of abt. 500 kW.

As the application of HTS in the rotor is a quasi-DC use case with small expected losses in the cold, we might choose an operating temperature of 30 K to get best benefit (critical current) from the HTS tapes.


This corresponds to a cooling penalty of 80 W/W. The conventional ohmic loss divided by the cooling penalty yields the maximum allowed loss in the cold of 6.3 kW.

This number is a high value for a DC-application of superconductors and it seems to offer a convenient approach to perform better than that.

So, the efficiency gain represents a high justification of HTS technology in the rotor of turbo generators.

How about low rpm generators? (see next slide)

Generators - WindPower



Lower frequencies facilitate HTS benefits (rotor and lateron stator(?))


10 MW turbine

Conventional
Assumed efficiency/ loss: 98% / ≈ 200 kW.

HTS
Operating temperature: $T_{op}=65$ K
Cooling penalty: x20 W/W
max. allowed loss: $200 \text{ kW}/20 \cdot 50\% = 5 \text{ kW}$

Hurdles:

- „New“ technology in **hard-to-access** locations
- Need for **AC-optimization** in stator!
- Multi-pole configuration
→ **complex cryogenics**



Unrestricted © Siemens AG 2018
Page 10 20181030 – Tabea Arndt Corporate Technology

Let's consider a 10 MW wind turbine.

A conventional generator would have a loss of abt. 200 kW.

As we would like to apply HTS in the stator (maybe in addition to applying HTS in the rotor) in an AC use case with some expected ac-loss in the cold, we might choose an operating temperature of 65 K to benefit from lower cooling "tax" of 20 W/W.

The conventional loss divided by the cooling penalty and a assumed benefit of 50% yields the maximum allowed loss in the cold of 5 kW.


This number is quite a challenge for an AC-application of superconductors and requires AC-loss optimized wires and designs!

In addition, it is hard to convince stakeholders in the wind power business to implement the "new" technology in sites which are hard to access (due to harsh weather and sea conditions offshore).

Furthermore, the required multi-pole configuration (in rotor and stator) might require complex cryogenics.

After having considered the power generation, now we proceed along the chain of power flow (see next slide).

Air core reactors vs. SFCL



Beneficial in terms of energy efficiency if cooling system is optimized, nevertheless new functionality.

10 MW devices

Air Core Reactor

Loss at nominal load: 3x 23 kW → 69 kW

HTS SFCL:



Operating Temperature: $T_{op}=77\text{ K}$

Cooling penalty: x14 W/W

max. allowed loss@ RT: 69 kW

max. allowed loss@ T_{op} : 69 kW / 14= 4.9 kW
(Challenge)

Loss of SFCL „ASSiST“ at Stadtwerke Augsburg, Germany: <21 kW*



Unrestricted © Siemens AG 2018

Page 11 20181030 – Tabea Arndt *: not optimized cooling system, biggest part of that independent of load

Corporate Technology

To handle potential fault currents without the need for technical maintenance after an incident, frequently air core reactor coils are used in conventional power technology (pictures in the middle).

A 10 MW setup (three phases) of air core reactors will show a loss at nominal load of 69 kW.

When aiming to shortcut the air core reactors with a HTS superconducting fault current limiter, one would shoot for a high operating temperature of 77 K to handle the high ac-loss with a small cooling penalty of 14 W/W.

In 2015, Siemens installed the SFCL “ASSiST” in the public grid of the Stadtwerke Augsburg, Germany (picture to the right)

This HTS device shows losses at room temperature level of less than 21 kW – even without optimized cooling system.

So, under nominal load, the loss is reduced to less than one third.


Nevertheless, the load curve (percentage of time being under nominal load and part load) will determine the overall yearly efficiency benefit.

But not to forget: the SFCL offers additional functionality: e.g. no voltage drop.

Due to the fact that the SFCL short cuts the air core reactors, there is a black-start capability possible.

The next device in the power chain could be a transformer, and –as we are heading towards “mobility”- we will consider a traction transformer (see next slide).


Transformers – traction transformers



HTS traction transformers meet the loss requirements while being much more compact and lightweight.

4.6 MVA transformer
(typically 1-phase, 16 2/3 → 60 Hz, ≈10 MVA)

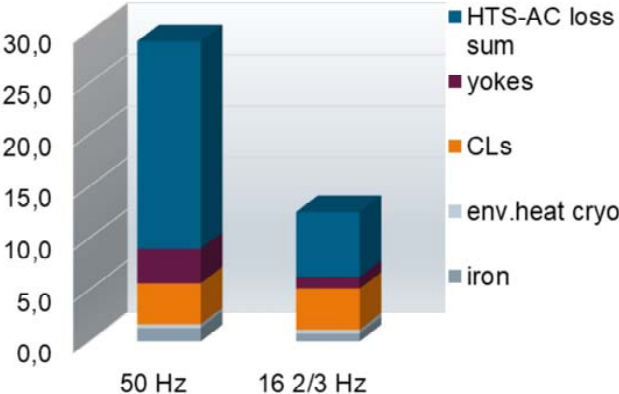
Conventional
Eff. / Loss: 92% / ≈368 kW



HTS

Operating Temperature: $T_{op}=77\text{ K}$
 Cooling penalty: $\times 14\text{ W/W}$
 (max. allowed loss@ T_{op} : $368\text{ kW}/14=26\text{ kW}$)
 HTS: 6.3 (16.6 Hz) ... 20.1 kW (50 Hz)
 Iron: 0.8 (16.6 Hz) ... 1.3 kW (50 Hz)
Total: <30 kW

Loss at room temperature of 4.6 MVA HTS traction transformer [kW]



Frequency	HTS-AC loss sum	yokes	CLs	env.heat cryo	iron
50 Hz	~20.1	~1.3	~6.3	~0.8	~0.8
16 2/3 Hz	~26.0	~1.3	~6.3	~0.8	~0.8

Unrestricted © Siemens AG 2018
Page 12 20181030 – Tabea Arndt
Corporate Technology

A typical traction transformer is a compromise of compactness and efficiency.

Therefore the low efficiency with quite high loss in a conventional device.

A transformer is clearly an ac-device

So, a high operating temperature of 77 K (cooling penalty of 14 W/W) should be chosen for the HTS device.

The loss is strongly dependent on the grid frequency (see graph with the components; a big share originates by the Current Leads CLs) but at a room temperature level clearly smaller (<30 kW) than for a Copper-based device (368kW) for nominal load.

In addition, the load curve of a train is usually quite beneficial (high percentage of time at nominal load).


A further advantage is the even more compact size of the HTS device.

A clear drawback is that due to the cooling needs, there is either no black start capability or a lead time before start, and there might be the need to introduce the new “consumable” liquid nitrogen into the daily operation together with training needs on technicians, new infrastructure etc.



The drive concept of the system “train” (locomotive, distributed traction or concentrated power cars) determines the wisdom to use HTS traction transformers.

Proceeding forward along the power chain, power transmission lines will be discussed (see next slide).

Power Transmission Lines – medium voltage AC cables



AC cables 10 kV	
Conventional	
Power	12.8 MVA
Loss	20 kW/km → 1.56 kW/(MVA km)
HTS	
Power	58 MVA
Op. Temperature:	77 K
Loss at 77 K:	1.5 kW/km (Env.heat) + + 0.5 kW/(km phase) (electr.)
Cooling penalty:	x14 W/W
Loss at RT:	42 kW/km → 0.72 kW/(MVA km)



Unrestricted © Siemens AG 2018
Page 13 20181030 – Tabea Arndt

Source: data sheet of cable suppliers,
M.Noë – „Ökonomie & Effizienz Supraleitender Systeme“, ZIEHL 2012

Corporate Technology

We will not touch the cables too deeply (refer to the IEA TCP HTS session this afternoon 2LOR3C for details).

As an example, we pick a 10 kV power cable, which shows a specific loss of 1.56 kW/(MVA km).

An AC application benefits from the higher operating temperature 77 K and the lower cooling penalty 14 W/W. So the HTS cable ends up with about half of the specific loss of 0.72 kW/(MVA km).

So for nominal load, half of the loss of the conventional cable is achieved.

In addition, HTS cables offer a much higher power to be transmitted in a smaller cross section.


However, at 10 kV, this means that the transport currents are much higher.

This might be difficult to be handled by present or available switchgear (switches and breakers).

Furthermore, a HTS cable has no black-start capability.

Nevertheless, for applications in mobility, there might be no more efficient and compact way to distribute the power.

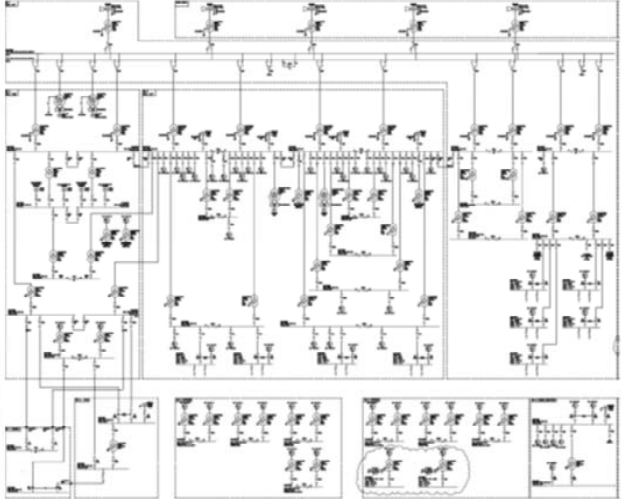

Floating Exploration Platforms



Island Grids offer an opportunity for HTS devices due to efficiency, weight, nominal load operation etc.

Transformers in Island Grids

Transformers on 33kV: 741,5 ton
Potential reduction by HTS-replacement: 370,75 ton
Alternatively removal of 33kV level!
(„Ampacity approach“)



Unrestricted © Siemens AG 2018
Page 14 20181030 – Tabea Arndt Corporate Technology

Combining the power cables and transformers might appear especially beneficial when considering large vessels, e.g. exploration platforms.

On such platforms, for high power transfer, there is a high voltage level of 33 kV introduced. Numbers and weight of the conventional transformers might sum-up to more than 700 tons.










1:1 replacement of the transformers by HTS technology could save abt. half the weight, which pays back in increased payload and more usable space.

By using the “Ampacity approach” (like the cable installation in Essen, Germany), one could get rid of the high voltage level.

The latter might be difficult to be handled by present or available switchgear (switches and breakers) due to the increased current levels.

Again, HTS devices have no black-start capability, but similar cooling technology is already installed on exploration platforms (liquefiers).

Having discussed some devices, we now turn into the field of mobility and take a different point of view.

Mobility									
									
	Bicycle	Car	Bus	Ferry (electr.)	Train (electr.)	Ship (PAX)	Aircraft	Truck	Ship (Cargo)
Example	-	4 seats	MB Citaro	Ampere	ICE4	Queen Mary 2	A320	40ton	Panama -6
speed [km/h]	20	80	80	18	150*)	50	820	80	15
Mass [ton]	0,1	2	19	≈2000	≈455	≈70000	≈90	≈40	≈112000
Dissipation [kWh/100km]	0,4	13	86	1281	430	214545	1392	1125	19309
Drag							L/D		
Rolling res.				n.a.	minor	n.a.	n.a.		n.a.
Water situat.	n.a.	n.a.	n.a.		n.a.		n.a.	n.a.	minor
PT-eff.	n.a.	20%	20%	90%	90%	30%	30%	30%	30%
Dynamics	n.a.			fixed			fixed		fixed

Unrestricted © Siemens AG 2018
 Page 15 20181030 – Tabea Arndt

*) 150 km/h is NOT a typical High Speed Train velocity

Corporate Technology

Having discussed some devices, we now turn into the field of mobility and take a different point of view.

The columns show –from left to right- increasingly complex vehicles and the two rightmost columns are dedicated to cargo vehicles.

The top rows of the table show details on the vehicle including a typical travel speed.

The 150 km/h for the electric train is NOT typical for high speed trains (so usually the dissipation is roughly four times as much).

The bicycle is somehow special as the vehicle mass is less than that of the passengers (PAX), dissipation is very small and energy efficiency is very high.

The bicycle is very instructive: the optimum speed is abt. 20 km/h. For that speed the dissipation is minimum and nearly equal by drag and rolling resistance.

This equilibrium of energy footprint of effect is common for a lot of vehicles.

The bottom rows show the main dissipation effects relevant for the vehicles (dark blue: relevant; light blue: relevant, but minor)

The energy efficiency and dissipation of ...

...road based vehicles is determined by drag, rolling resistance, efficiency (of fuel based) power train "PT" and by the dynamics (acceleration and deceleration processes),

...trains is dominated by drag (especially for high speed trains!) and dynamics (in case of fuel based locomotives, switching to electrical power trains is strongly recommended),

...ships is dominated by water drag, the water situation (waves, water depth, underground, streams,...) and dynamics.

As an important nota bene it has to be stated, that for ferries, aircrafts and cargo ships the dynamics is mainly fixed by the scheduled mission profile.

So, the table gives some fingerprints for the selected vehicles.

How about the corresponding power and energy needs? (see next slide)

Mobility		SIEMENS Ingenuity for life						
	Car	Bus	Ferry (electr.)	Train (electr.)	Ship (PAX)	Aircraft	Truck	Ship (Cargo)
Time to cruising*)	10 s	20 s	1 min	2 min	2 min	30 min	45 s	2 h
Power to cruising*)	50 kW	235 kW	410 kW	3,3 MW	56 MW	5,4 MW	220 kW	7,2 MW
Efficiency of Power Train	20%	20%	90%	90%	30%	30%	30%	30%
Net fuel for 1000 km trip [l/100km/PAX]	1,61 (6,4 l/100km)	0,90	0,40	0,11	23,86	3,08		
CO2-equivalent [kg/100km/PAX] [g/km]	4,3 173	2,6	REN 0,0 Fuel 1,2	REN 0 Fuel 0,3	556	8,5		

*) power need to accelerate/ decelerate the vehicle in the given time to/ from cruising speed

Unrestricted © Siemens AG 2018
 Page 16 20181030 – Tabea Arndt Corporate Technology

Giving some typical timescale for acceleration, one can estimate the power need to get to cruising. This power need is not 1:1 related to the de facto installed power in a vehicle, but simply needed for the given acceleration.

It seems to be quite typical for a small car and reasonable for busses and trucks (comparable to minimum regulations requirement).

Nevertheless, the installed power in trains, aircraft and cargo ships might be higher than that.

The power train efficiency values are not carved in stone, but reasonable base for further discussions.

When considering a non-stop continuous 1000 km trip, then the energy need can be converted in a fossil fuel consumption in units of l/100km/PAX and finally in a CO2-equivalent (in case the electric power is generated by renewable energy the CO2-footprint vanishes).

The fuel consumption of the car seems reasonable when comparing with daily life.

The energy efficiencies of bus, (electr.) ferry and train (keep in mind the small speed of 150 km/h) are higher.

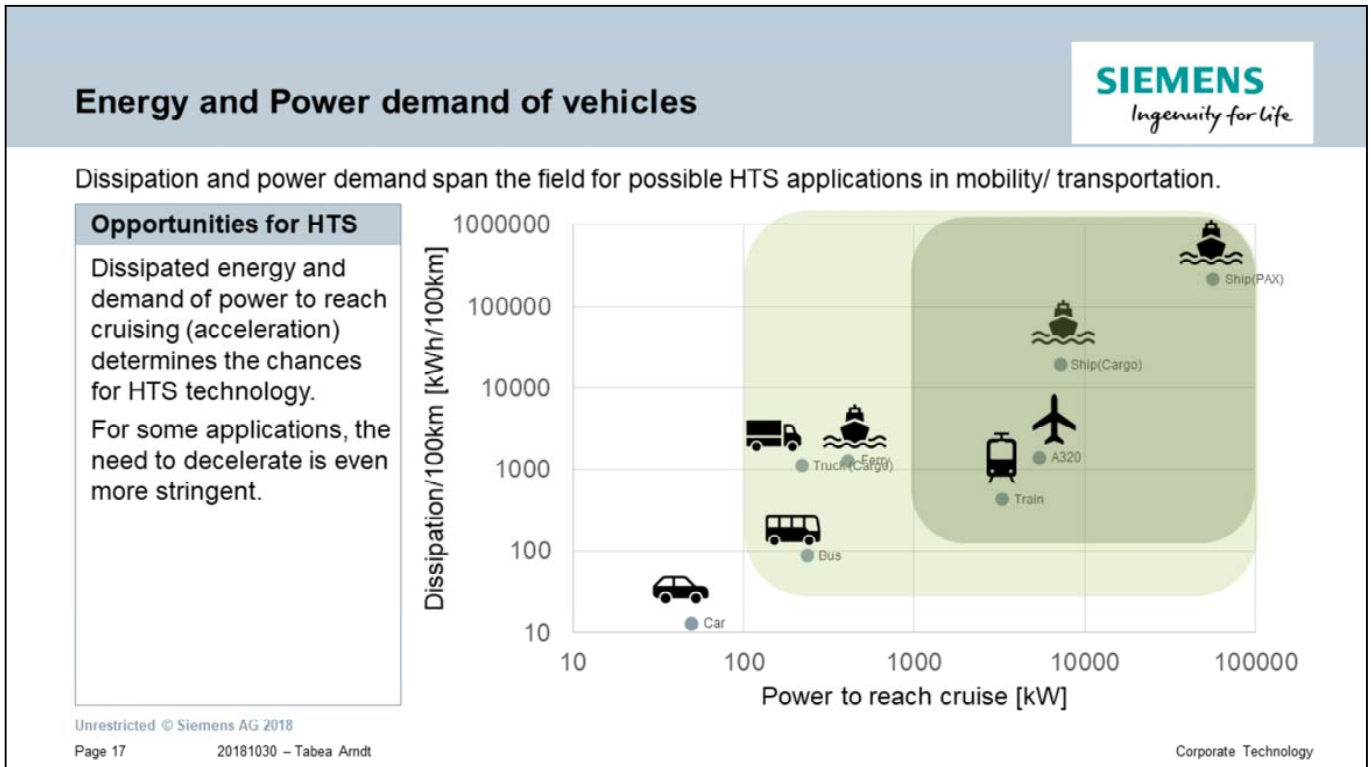
Worst is the cruise ship due to the fact that it is not only “mobility” but more or less moving “complete towns” around.

The fuel consumption of a fully booked aircraft is really good (value in accordance to typical values of airlines for long distance travel); a fully booked aircraft is more efficient than a 2 PAX car.

Tables are hard to read, so how to get some advice for HTS technology out of that?

The green marked cells give some hints. (see next slide)

N.B.: From 2020 on, in Europe a maximum CO2 emission of 95 g/km is allowed for new cars. From the above table you can see that the only chance to achieve that is by a dramatic increase in PT efficiency and/ or avoiding Carbon-based fuels. The limits by law of 2020 will decrease to 2030 even more.



An important indicator for the usefulness of HTS technology in vehicles is the physical power demand.

Due to the basic power need of the cooling technology (cold heat loads time cooling penalty) there is a present minimum threshold of abt. 1 MW power need of the vehicle (dark green regime).

Future HTS technology (e.g. with improved performance and/ or reduced AC loss) might reduce the threshold to abt. 100 kW (light green regime).

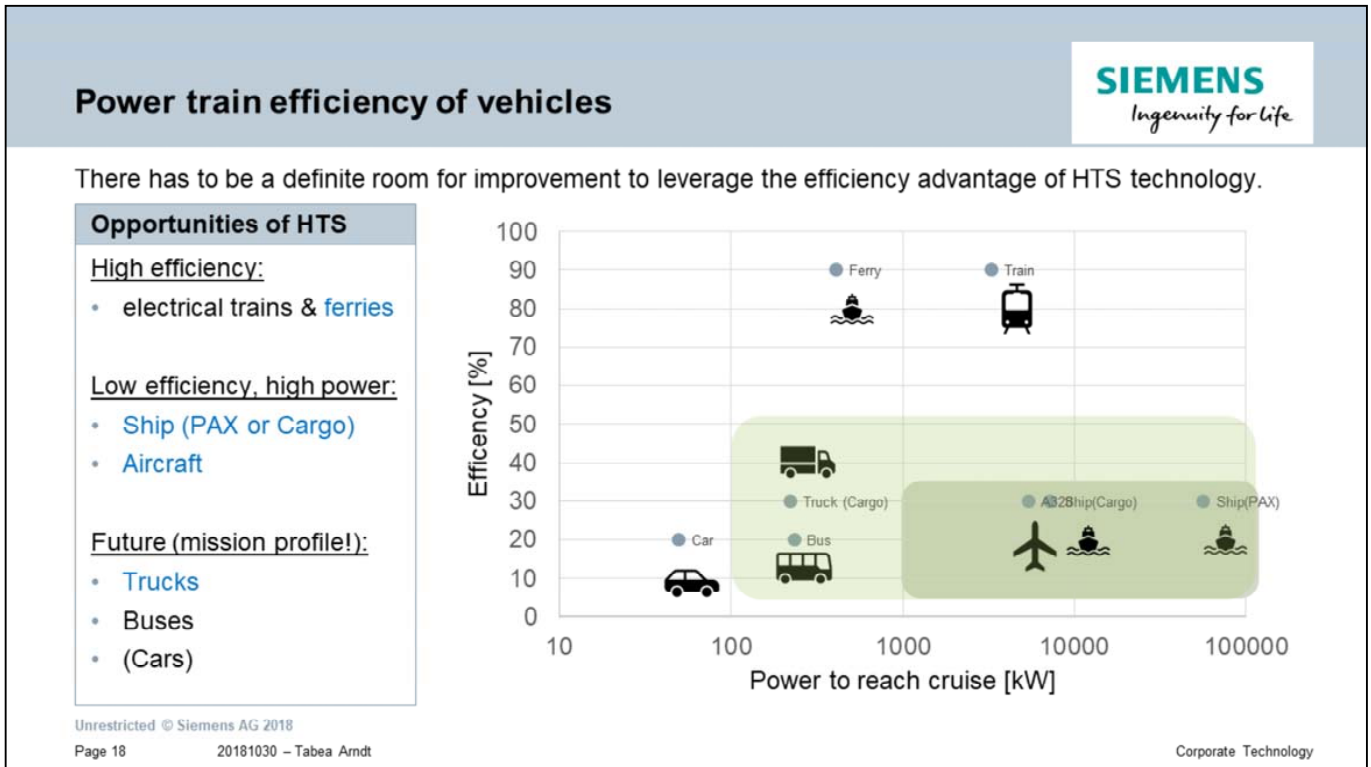
In addition, the dissipation should be high enough to offer some room for improvement by HTS technology.

This graph shows if there is a window of opportunity for HTS technology to enter the vehicle.

The width of this window of opportunity may be determined by the possibility to increase the efficiency (see next slide).

Nota Bene:

The power demand of some vehicles is not determined by the acceleration need, but by the deceleration. So, for example, for an electric car, for recuperation reasons during acceleration, a power of abt. 1 MW would be suitable to convert the kinetic energy back into a battery.



Here again, two regimes of opportunity are indicated.

As the efficiency of electric ferries and trains is already very good, a considerable improvement in energy efficiency is mainly seen for aircrafts and big ships.


Again, when performance and/ or AC loss are improved, then big road based vehicles might follow.

Nevertheless the mission profiles and utilization of the vehicle has to be considered, too. Frequent operation in cruising speed is supporting the use of HTS technology.

For the blue marked vehicles (textbox) we will supply some more details in a few seconds.

We will start with the electric ferry (see next slide).

E-Ferry

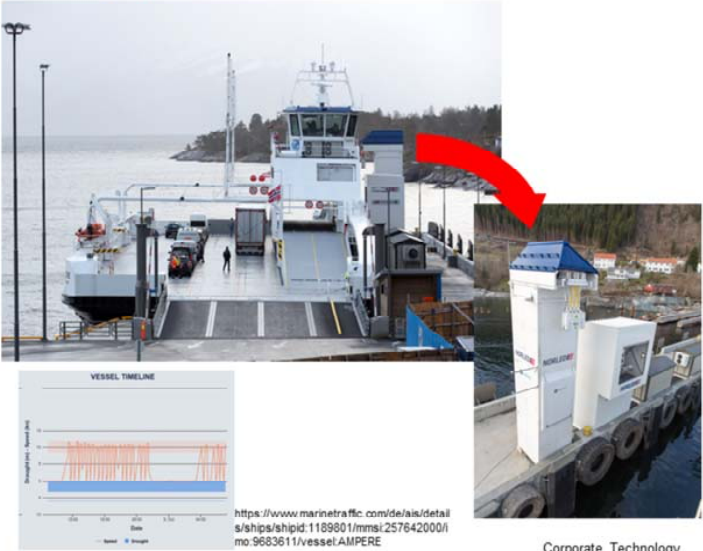


Clever electrification of ferry boats: saving 10^6 liters of fuel per year

E-Ferry Ampere

Vessel:	catamaran (Al instead SS)
Length/ width:	80 m / 20 m
Propulsion:	0.9 MW = 2x 450 kW (electric)
Payload:	199 ton
PAX:	360
Distance:	6 km (in 20 Minutes) Lavik-Oppedal, 34x/day
Energy/trip:	150 kWh
Battery:	260 kWh (\approx 10 ton)

Other ferry connections to follow.



<https://www.marinetraffic.com/de/ais/detail/s/ships/shipid:1189801/mmsi:257642000/i/mo:9683611/vessel:AMPERE>

Unrestricted © Siemens AG 2018Page 1920181030 – Tabea ArndtCorporate Technology

The electric ferry Ampere replaces a fuel-driven ferry and saves quite a lot of fuel and CO₂.

The ferry is based on a lightweight design of the vessel with onboard batteries and an electric drive train.

The onboard battery is re-charged by special charging stations with buffer batteries at the jetty (right picture).

The buffer batteries have been installed because the electric power grid would have been too weak to supply the required charging current.

The mission profile of this ferry would have been very attractive for the use of HTS technology (middle bottom).

Nevertheless, remembering the previous slide, the efficiency of the conventional electric ferry is already good, and so the gain by HTS technology small.

E-Highway – project in Sweden by Scania & Siemens

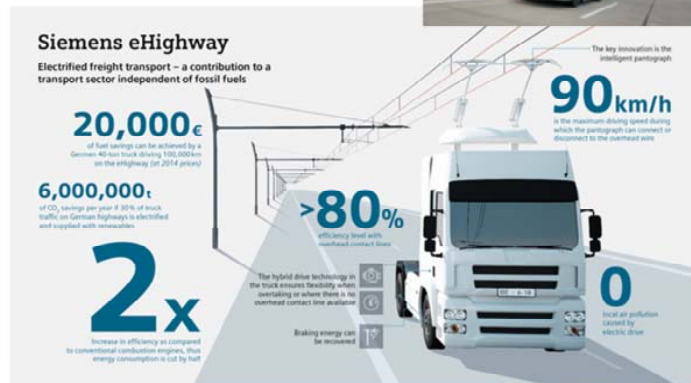
SIEMENS
Ingenuity for life

Hybrid trucks to move forward to electrified transportation of goods without local pollut

Details

In 2030, the Swedish transport sector should be free of fossil fuel.

The hybrid truck with intelligent pantograph (allowing overtaking and flexible connection at high speed) is a significant step towards that goal.



Unrestricted © Siemens AG 2018

Page 20

20181030 – Tabea Arndt

Corporate Technology

Sweden is working towards a fossil fuel free transport sector.

Scania and Siemens have a joint project in testing a parallel hybrid truck with intelligent pantographs.

This allows to travel long distances by electric motors, and local delivery by the combustion machine.

A similar project is ongoing in California in an industrial environment.

The next step could be a serial hybrid truck or a purely electric truck.

E-Ship – HTS generators/ motors, transformers & cables

SIEMENS
Ingenuity for life

CO₂- and sulphur-caps on emissions by ships set by the IMO and others challenge the presently oil-driven

Details

- HTS Motors / Generators:
 - highest efficiency
 - reduced volume & weight
 - excellent stability and power quality
- HTS Transformers and Cables:
 - compact, lightweight and efficient, reduction of devices
- Trend to LNG-driven cruise liners
(e.g. worldwide cruise ship based on LNG “AidaNova” starting on 02.Dec. from Hamburg, Germany)
 - beneficial power generation by gas turbines
 - “electric shaft”
 - entry point for HTS technology



HTS motors and generators offer the general benefits of HTS machines and some advantages on system level in addition to that (e.g. new design freedoms).

Other HTS devices might be introduced as well as discussed before.

Policy and regulations are starting to set some emission thresholds on ships.

This regulations are setting a trend to more “green” ships, e.g. LNG-driven cruise ships.

And this application field is not too far from the present base of technology (see next slide).

Rotating machines for ships



HTS motors for ship propulsion (based on 1G-HTS at time of construction)

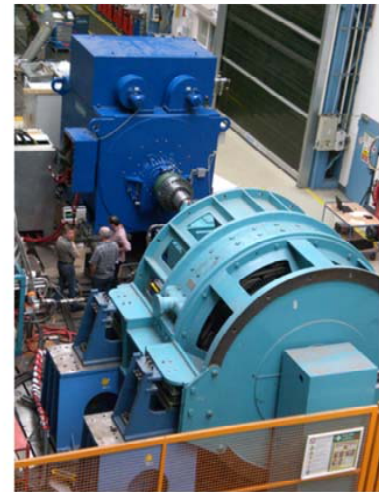
1L0r1B-01: Peter O'Brien, QUT
"Test environment for study of
HTS electric machine
performance under dynamic
electromagnetic conditions"



HTS1 Motor, 400 kW (2002)
(presently at QUT)



Amsc Motor 36.5 MW (2007)



HTS3 Motor, 4MW (2008)

Unrestricted © Siemens AG 2018

Page 22

20181030 – Tabea Arndt

Corporate Technology

Several companies have already built, tested and operated motors and generators based on HTS technology with different power ratings and specifications for the application on ships.


The shown examples are still based on the 1G-HTS (Bi-2223).

For testing of the HTS1 machine outside of Siemens, please refer to the talk 1L0r1B-01.

These machines could be build much more powerful and efficient with todays 2G-HTS (RE-123).

Finally we will discuss the „kings-class“ of vehicles: electric aircrafts (see next slide).

Electrification in Aviation (propulsion)

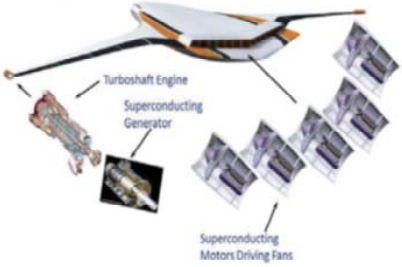
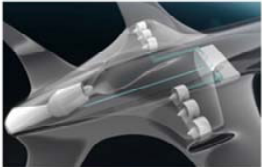



Electrified aircrafts enables more **sustainable aviation**

Aspects

Transport efficiency $\propto \left(\frac{\text{Lift}}{\text{Drag}}\right) \times (\text{Power Train Efficiency})$

- less **noise & emissions**
(Green Hous Gases, target “European Flightpath 2050”: -75%)
- higher **efficiency** in propulsion
- new **degrees of freedom in design**
- reduces “**over-the-top design**”
- “**decentralization and decoupling**” of power generation and propulsion



Corporate Technology

Unrestricted © Siemens AG 2018
Page 23 20181030 – Tabea Arndt

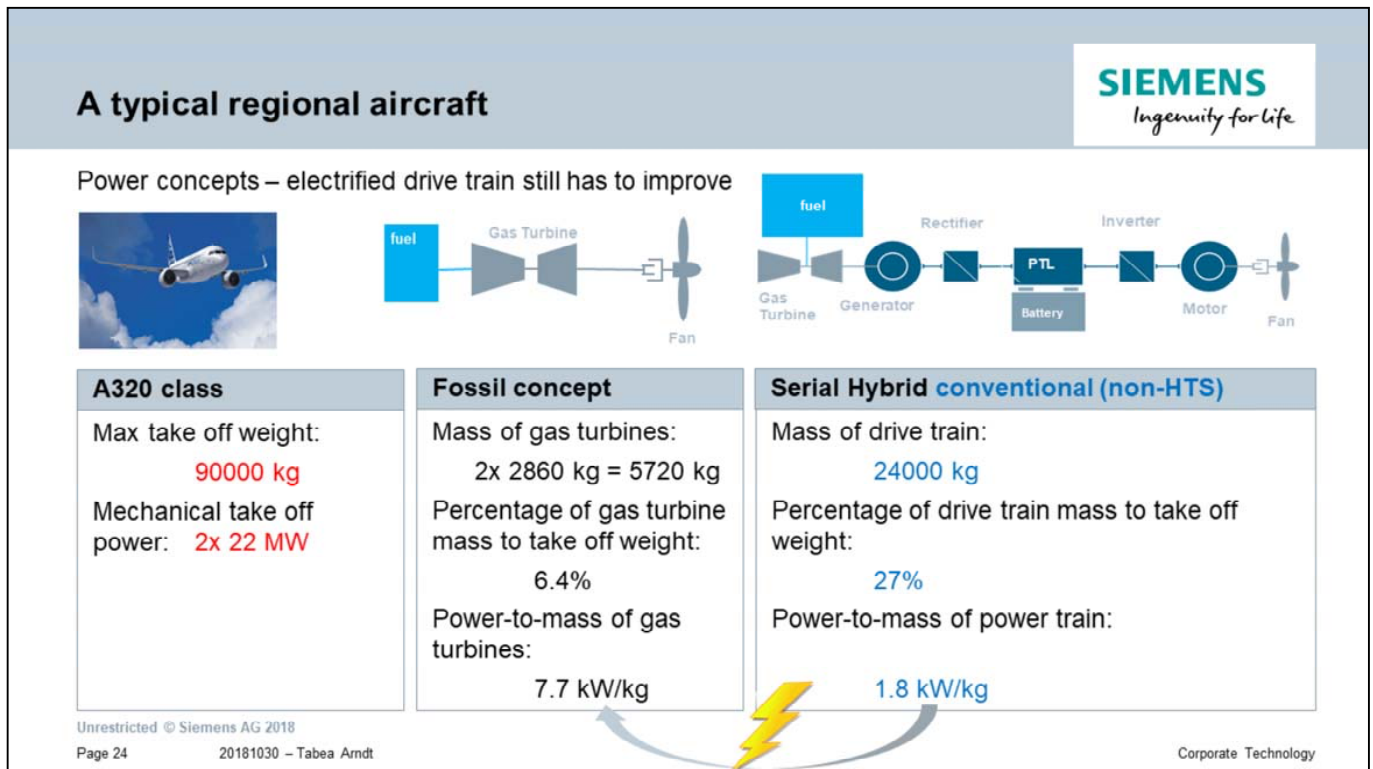
Electrification in aviation is not a goal by itself, but is contributing to turn the quite efficient aircrafts in even more sustainable vehicles:

Electric aircrafts are quite unique as vehicles as the efficiency is simply proportional to the product of Lift-to-Drag (L/D) and Power-Train-Efficiency.

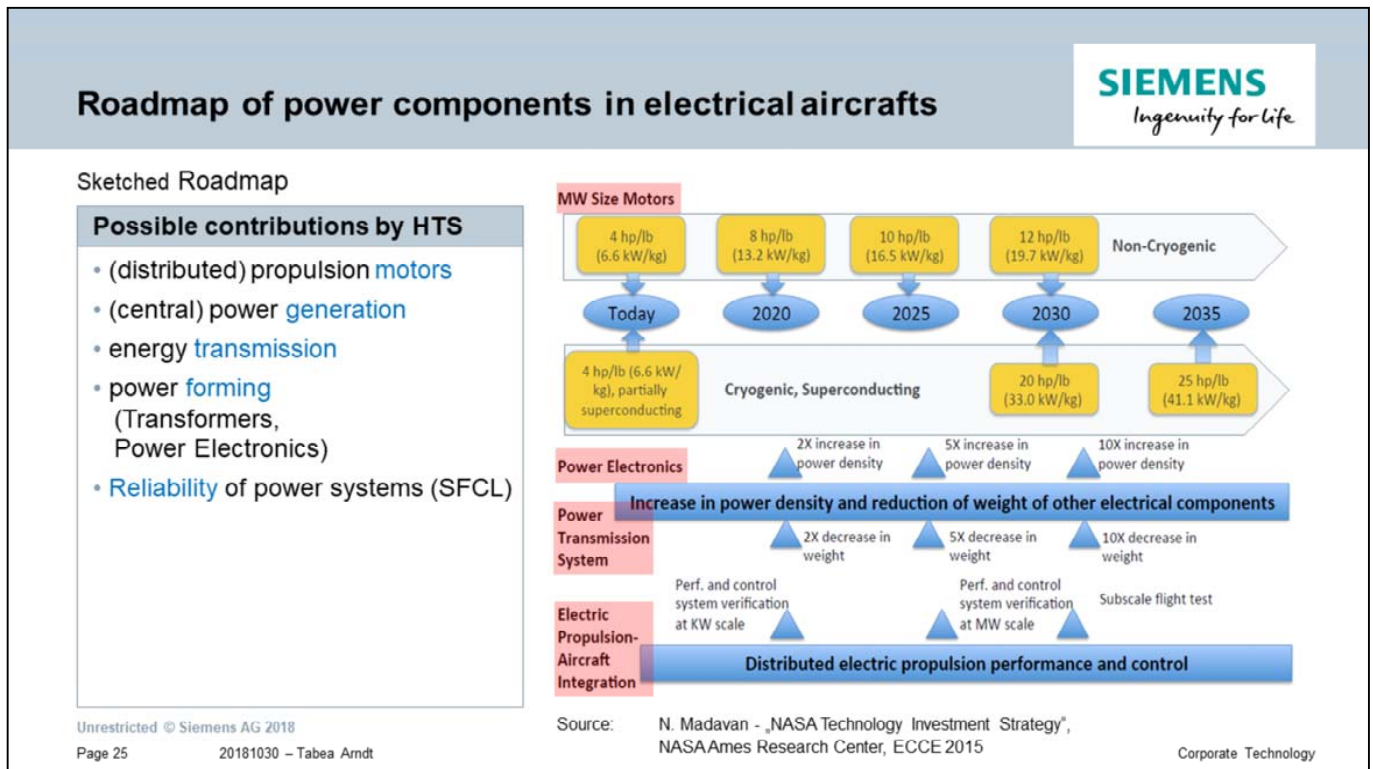
The present aircrafts are very well optimized to a high extend and drastic improvement in L/D is not to be expected without a dramatic change in the airframe.

Nevertheless, emissions and noise have to be reduced (refer to Flightpath 2050 and Cleansky). Electrification of aircrafts is introducing the concept of decentralization and decoupling of power generation and propulsion (see two bottom pictures right) and/ or new design options (right top).

When looking at regional aircrafts, which figures of merit have to be addressed? (next slide)



As an example we pick a regional aircraft having a mechanical take off power of two times 22 MW. The conventional fossil propulsion reaches a power-to-mass-ratio of abt. 7.7 kW/kg. When introducing a serial hybrid (based on conventional technology), one reaches abt. 1.8 kW/kg. This is clearly underperforming and not sufficient to electrify the propulsion. So, what has to be done in the field? (see next slide)

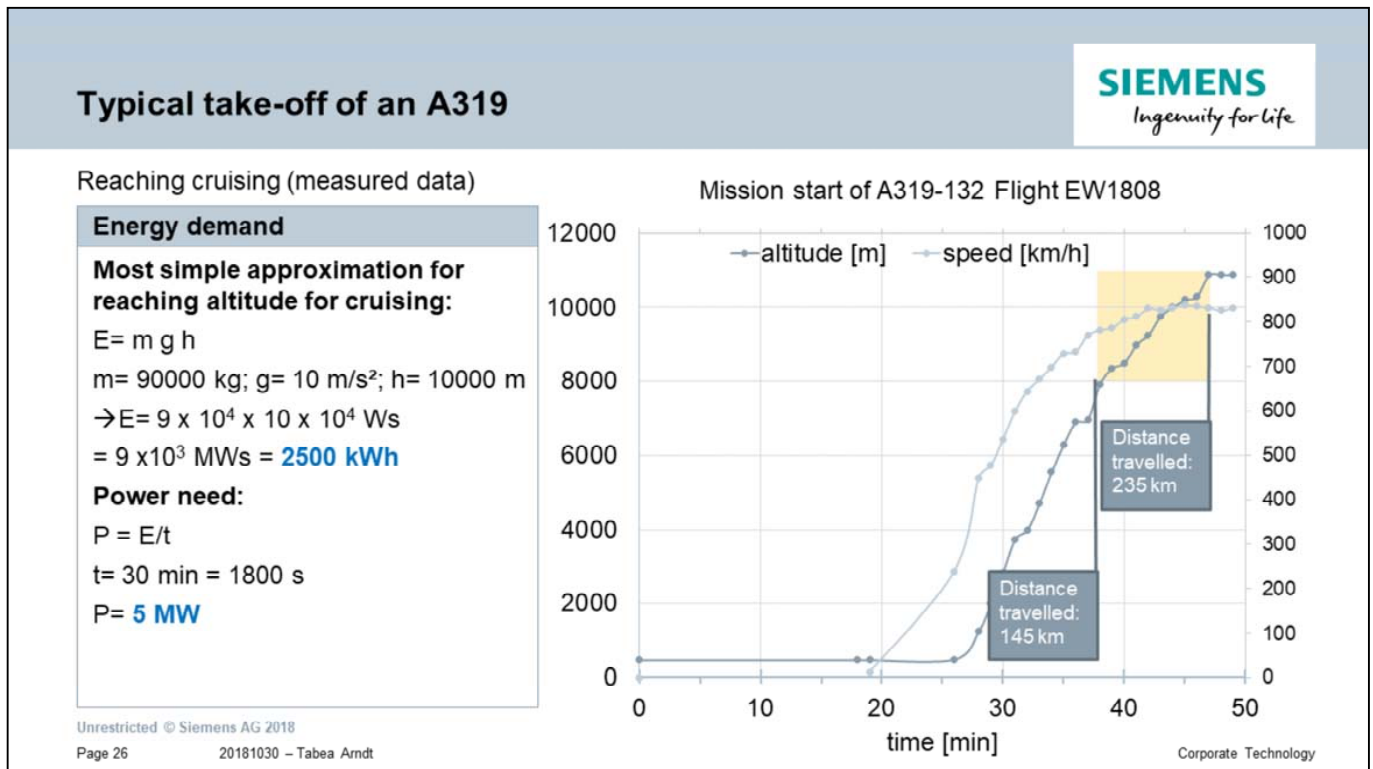


When borrowing from the NASA there is a roadmap sketched.

From that it follows that the power-to-mass-ratios of motors, generators and overall distribution system have to be improved.

Furthermore, the non-cryogenic motors might not reach a value of higher than 19.7 kW/kg; cryogenic or superconducting devices will be required.

In addition there are some specific aspects in the (fixed) mission profile to be considered (see next slide).



Again let's consider a regional aircraft.

To reach the cruising altitude a very simple physical estimation yields a power need of 5 MW (neglecting drag, streams, strong winds,...).

This is in contradiction to the installed mechanical take-off power of 2x 22 MW!

Is this estimation too simple?

Not too much.

The graph shows the data (real measurements on a real flight) of speed and altitude in the first 50 minutes after push-back of the aircraft.

The yellow rectangle highlights 10 minutes (abt. 100 km) of flight – the last 10 minutes of the climb towards cruising altitude.

The next slide will follow-up on that.

Power loss of turbines with increasing altitude (approximation)

SIEMENS
Ingenuity for Life

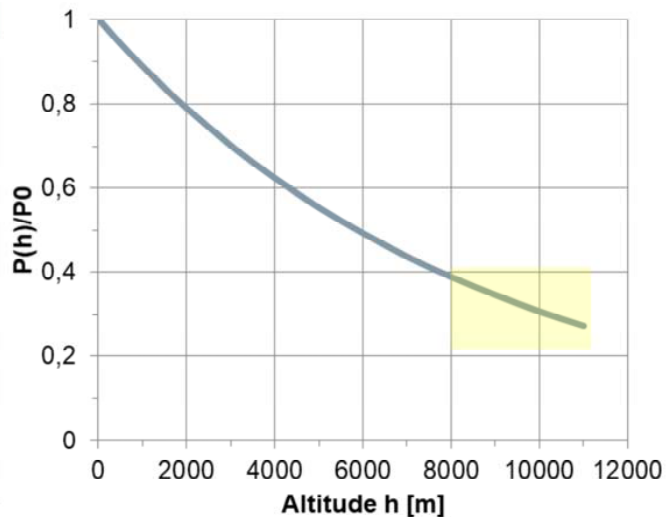
Last minutes of climbing determine turbine power design

Restricted window for propulsion design

Turbines driven by fossil fuels have to deliver sufficient power even just before reaching cruising altitude – this means for the operation of **5...10 minutes** of the overall travel time!

During this period the remaining power is abt. **30%**

In case of the A320:
2x 22 MW → 2x 7 MW



Unrestricted © Siemens AG 2018

Page 27

20181030 – Tabea Arndt

Corporate Technology

The graph shows (schematically) the loss of delivered power of fossil turbines with increasing altitudes.

In the last 10 minutes of climb, the mechanical take-off-power reduces to abt. 30%.

So, in the yellow rectangle the designed power reduces to about 7 MW per turbine.

For safety reasons and margins, redundance and considering the formerly neglected effects (drag, winds,...) this is well into agreement with the estimated 5 MW.

Knowing that, there is a clear need to “overdesign” the turbine power ratings.

Are there other special aspects in aviation? (see next slide)

Special challenges in regional aircrafts

SIEMENS
Ingenuity for Life

Selected aspects

Power demand >10 MW

On ground: 11 kV to 33 kV would be chosen

Insulation strength

Paschen-Effect: difficult to use >270 V
at high altitudes (270V, air, ≈1 cm mbar, ≈4000 m altitude).

Power-to-weight >33kW/kg

Reduction of mass is a must

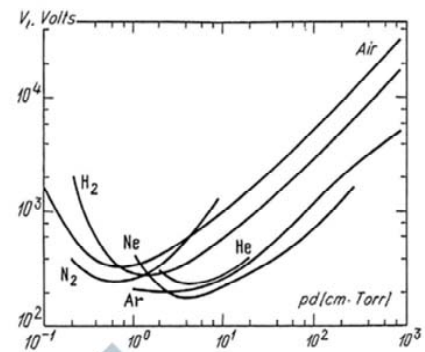
Heat removal/ cooling

"Thin air": dramatically reduced capacity of heat removal by convection/ air cooling.

Mission profile

The highest power demand is during climbing and descent;
during cruising there is only part load operation (abt. 30%).

Paschen-curve for selected gases



270 V, air, ≈1 cm mbar
≈4000m alt.

We have learned that the power demand of regional aircrafts is clearly above 10 MW. On ground, a medium voltage level (11...33 kV) would be suitable for that.

But due to the Paschen-Effect, aircraft designers prefer to stick to low voltages; today moving away from the former 270V to abt. 1.5 kV is discussed.

From the NASA roadmap we might require a power-to-mass-ratio higher than 33 kW/kg.

A further aspect is the difficulty to get rid of heat in thin air at high altitudes – so every Watt heat not produced will not add additional cooling capacity to the aircraft (which might produce additional drag).




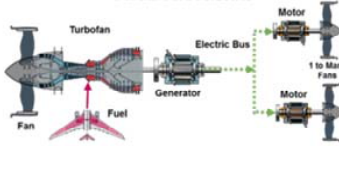
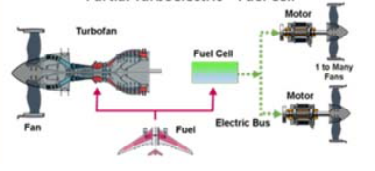
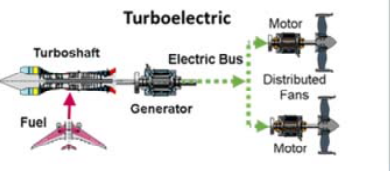
The mission profile is quite fixed (climb quickly to cruising altitude) and determines the "overdesign need" of the turbines.

There is already some concept work ongoing (see next slide).

NASA

SIEMENS
Ingenuity for life

Aircraft System Studies

STARC-ABL	Boeing SUGAR Freeze	NASA N3X
<ul style="list-style-type: none">• 7-12% less fuel• advanced 2...3 MW power system, turbogenerator• BLI	<ul style="list-style-type: none">• 56% fuel reduction• Superconducting aft fan motor• BLI	<ul style="list-style-type: none">• 70% fuel reduction• Superconducting distributed 50 MW• Hybrid Wind Body
		
<p>Partial Turboelectric</p> 	<p>Partial Turboelectric – Fuel Cell</p> 	<p>Turboelectric</p> 

Page 29

20181030 – Tabea Arndt

From R.H.Jansen - <https://ntrs.nasa.gov/search.jsp?R=20180000402>

2018-08-31T08:52:53+00:00Z

Corporate Technology

NASA and partners conducted some system studies.

From left to right the studies become more (turbo-)electric in propulsion.

The airframe design may be adopted due to the new power train to increase the L/D-value by addressing the Boundary-Layer-Ingestion (BLI).

Superconductivity might help in design freedoms as well as in power train efficiency, so improving both factors of transport efficiency of aircrafts (L/D and power train efficiency as discussed before).


There are not only concept studies, but projects on specific devices and aspects (see next slide).

In Germany, there is the funded project “TELOS” focusing on the power generation, distribution and propulsion motors.

Partners are Airbus, KIT and Siemens.

In Germany, Siemens has an in-house project working on the power generation itself (see next slide).


Siemens e-Aircraft – Current Research on HTS-machines for electric propulsion



Research of innovative technology for electric machines (10 MW HTS generator for hybrid electric flight)

Industry standard


≈0.45 kW/kg



eCar PM

≤1 MW


≈2...3 kW/kg



eAir PM


→o(100) kW

≈5...6 kW/kg



HTS generator for eAircraft


→33 kW/kg



HTS-2

4 MVA / 3600 rpm

≈0.6 kW/kg (7t)



	Power [MW]	p.f.	Voltage [kV]	Speed [rpm]	Shaft Height [mm]	Weight [kg]	Power-to-mass [kW/kg]
HTS-2	4	0.9	6.6 (rms)	3600	500	≈7000	0.6
	x 2,5			x 2		/14	x 33
eAir	10	n.a.	<1.5 (peak)	7000	≈300	<500	>20

Unrestricted © Siemens AG 2018
Page 31
20181030 – Tabea Arndt
Corporate Technology

Siemens has quite a history in electric machines starting within the field of industry, via electric cars (PM=permanent magnet machines) and general aviation aircrafts – all based on conventional technology (from left to right).

Siemens has experience in building HTS-Generators for ground- or ship-use, too (the HTS-2, right picture).

The table shows, which improvements are needed to get from the HTS-2 machine (based on 1G-HTS) to a first HTS-generator for electric aircrafts (based on 2G-HTS).

And there are some projects on European Scale (see next slide).

Nota Bene: All values given on this slide are including excitation system, inverters, dedicated cooling system, back iron, housing etc.













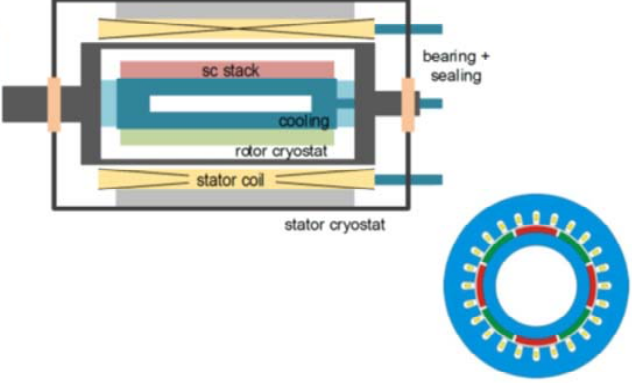
ASuMED – Advanced supercond. Motor Experimental Demonstrator

SIEMENS
Ingenuity for life

EU-funded, Horizon 2020, 3yrs, started May 2017, 4'8€

Demonstration of 20kW/kg

- develop a 2G-HTS stator >450kA/m (distributed winding, LH₂-cooling)
- Rotor: 2G-HTS stacks (average >2.5 T)
- integrated magnetization system in stator
- highly efficient cryostat
- integrated cooling system & power converter
- 1 MW power at 10.000 rpm
- thermal loss <0.1%
- innovative modular inverter topology with enhanced failure protection



Page 32 20181030 – Tabea Arndt Corporate Technology


The project “ASuMED” targets a challenging fully superconducting HTS/PM concept.

The rotor uses a stack of 2G-HTS permanent magnets, the armature winding will be realized using 2G-HTS tapes.

Other system aspects will be covered, too.

Let's conclude (see next slide).

Conclusions



Efficient and sustainable mobility – HTS may contribute

Returning to the trident spikes	Mobility & HTS
<ul style="list-style-type: none">ψ Cost: reduction by<ul style="list-style-type: none">• performance increase• economy of scale.ψ Present Tc's: no show-stopperψ Cooling Technology:<ul style="list-style-type: none">• tiny dissipation• Cooling penalty vs. loss of conventional device	<ul style="list-style-type: none">• Sustainable mobility needs vehicles with low/ no GHG emissions.• The electrification of vehicles offers solutions.• Pronounced opportunities for HTS technology show-up when<ul style="list-style-type: none">ψ there is room & need for efficiency improvementψ the mission profile/ utilization is appropriateψ specific benefits of HTS technology are crucial (e.g. power-to-mass, space restrictions/ compactness, dynamics, stability, etc.)• Further opportunities might open up when HTS tapes for use in AC fields of small or medium amplitudes are available. <p>The future of mobility is in efficient vehicles used in a sustainable way – there is a strong need in educational efforts</p>

Unrestricted © Siemens AG 2018Page 33 20181030 – Tabea ArndtCorporate Technology

It's important to re-address the issues of the trident brought up by engineers not deeply into superconductivity.

And one might turn the three issues into three beneficial aspects for HTS:

- efficiency improvement
- mission profile/ utilization
- specific benefits

Nevertheless there is still need for R&D and improvement, e.g. in the field of AC use (optimized HTS tapes with reduced ac loss).

And it is mandatory to perform some educational efforts – especially out of the “comfort zone” of superconductivity.

This might be done by publishing not only in “superconductivity journals”, but in “Electrical Engineering” or others.

Acknowledgements



K. Rajashekara – Uni Texas at Dallas
R.H. Jansen - NASA
A. Bender - KIT
S. Grohmann - KIT
M. Noe - KIT
T. Reis, J. Oswald - Oswald
Partners from Airbus
Colleagues from Trench
Colleagues from Siemens
Lufthansa

I deeply thank for contributions and discussions with quite a lot of people – here is a subset.

**Thank you –
Questions?**



Tabea Arndt

Principal Key Expert “Electromagnetic Systems”
CT REE ELM

Günther-Scharowsky-Straße 1
91058 Erlangen

Phone: +49 (9131) 17-36977
Mobile: +49 (172) 1489887

E-mail:

Tabea.Arndt@siemens.com

siemens.com/corporate-technology

Intranet

intranet.ct.siemens.com

Unrestricted © Siemens AG 2018

Page 35

20181030 – Tabea Arndt

Corporate Technology

Thank you for your attention!