Sustainable Transportation and Electrical Power Systems

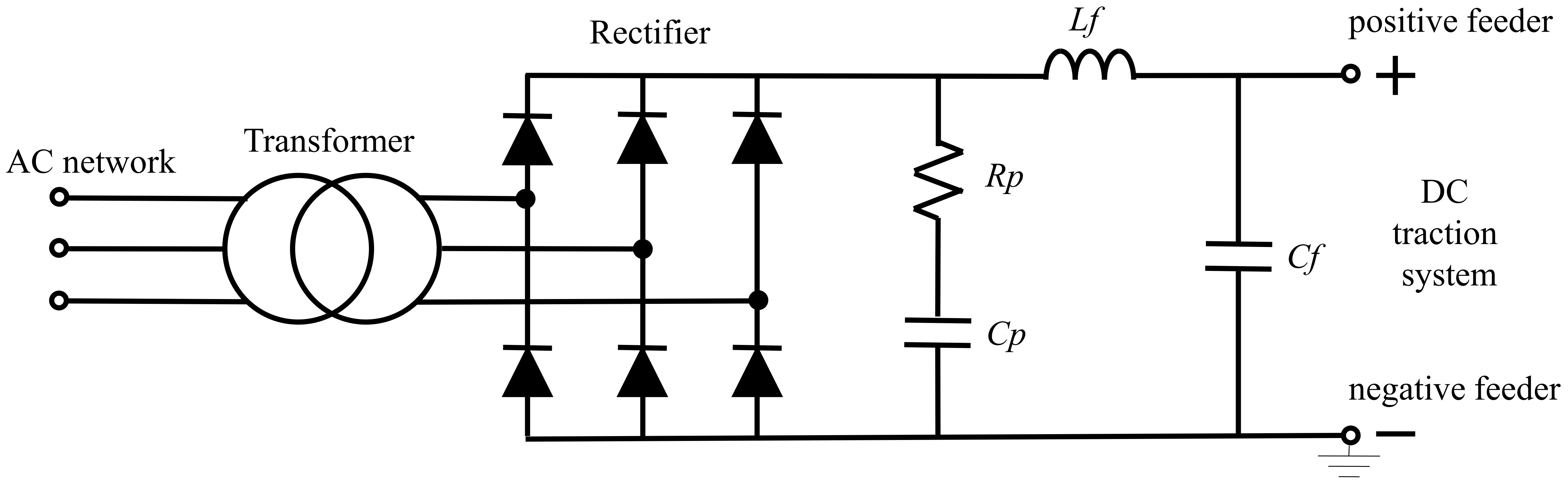
Universidad de Oviedo

Lesson 2 – DC Railway Systems

Semester 3 – Advanced Simulation of Railway Power Systems

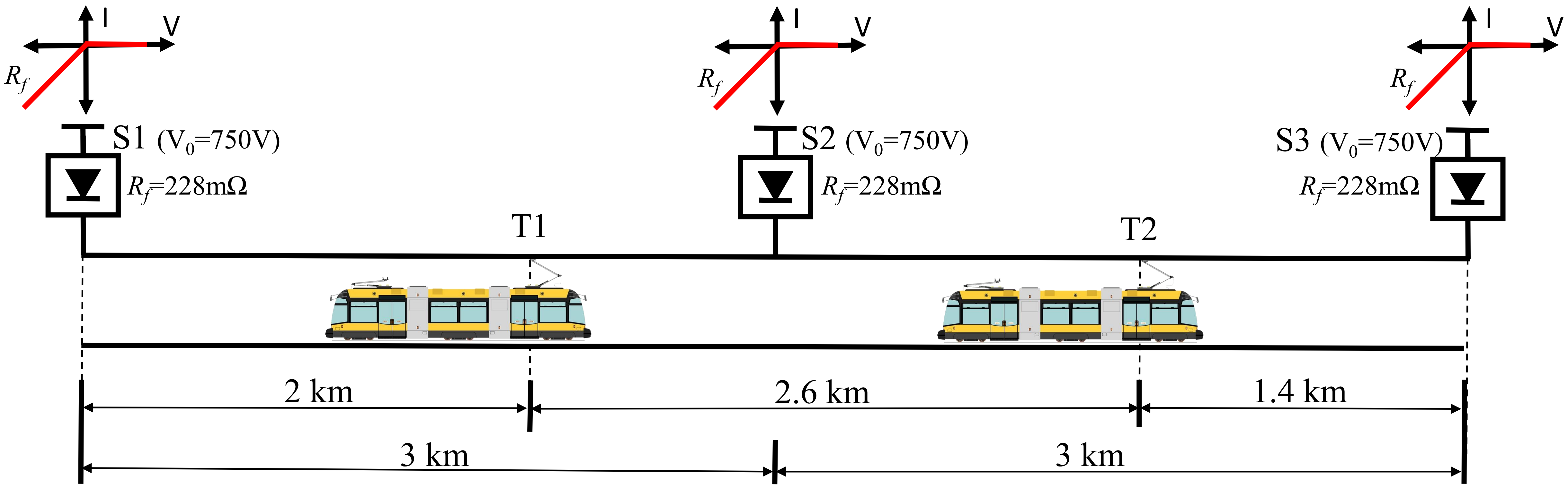
Lecturer: Pablo Arboleya Arboleya

Traditional DC traction systems for light railways



Single group non-reversible conventional substation

Conventional DC scenario



Positive feeder: $R_p = 51\text{m}\Omega/\text{km}$

Negative feeder: $R_n = 14\text{m}\Omega/\text{km}$

Train max. traction and braking power (0,65MW)

Substations rated power: $P_r = 0{,}35$ MW

No load and rated load DC voltage: $V_0 = 750\text{V}$, $V_n = 700\text{V}$

Power transformer s.c. voltage: $V_{cc} = 8\%$

Cases of study (Summary)

	Substations ****	Trains Acc. ***	Train controls **	Pref T1 *	Pref T2 *
Case 1	Non-reversible	No	No	650	350
Case 2	Non-reversible	No	No	-650	564
Case 3	Non-reversible	No	Yes	650	350
Case 4	Non-reversible	No	Yes	-650	474
Case 5	Reversible	No	Yes	650	350
Case 6	Reversible	No	Yes	-650	474
Case 7	Non-rev + Acc	No	Yes	650	350
Case 8	Non-rev + Acc	No	Yes	-650	474
Case 9	Non-reversible	Yes	Yes	650	350
Case 10	Non-reversible	Yes	Yes	-650	474

* Negative reference power in the trains means that the train is braking and regenerating

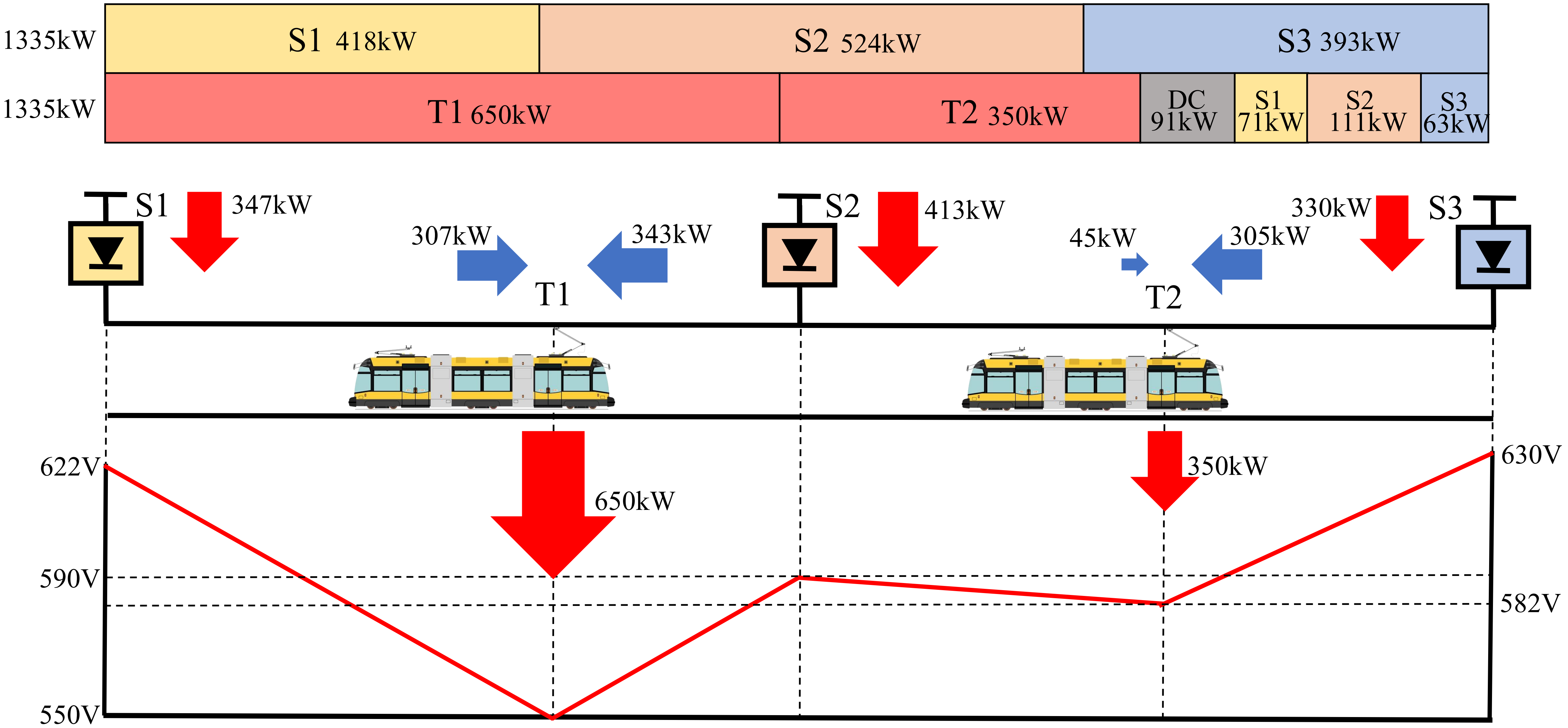
** The considered train controls are the overcurrent protection and the overvoltage protection or squeeze control

*** Trains equipped or not with on-board accumulation system

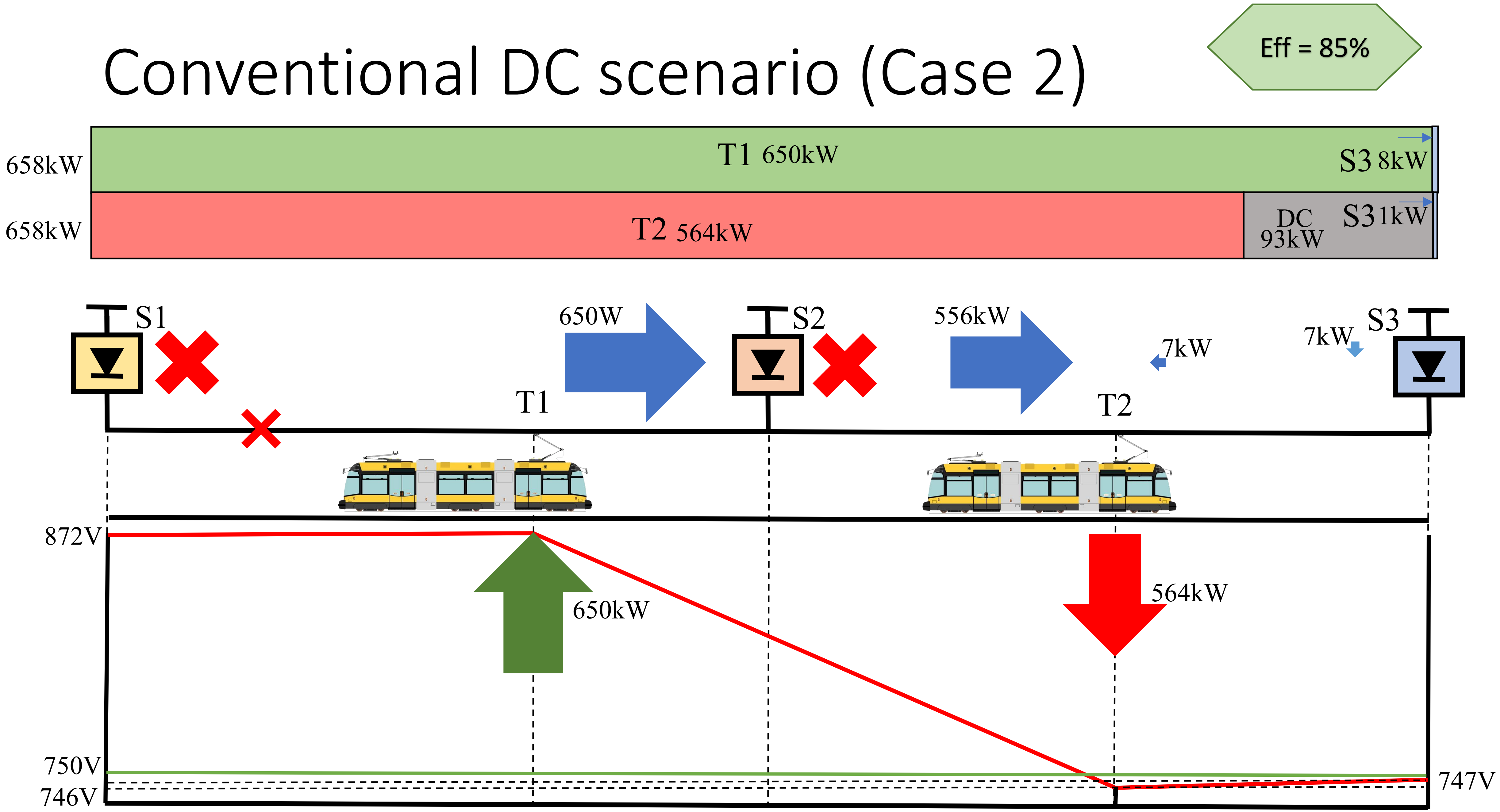
**** The substations can be conventional (non-reversible), reversible (with dead band) and non-reversible with off-board accumulation

Conventional DC scenario (case 1)

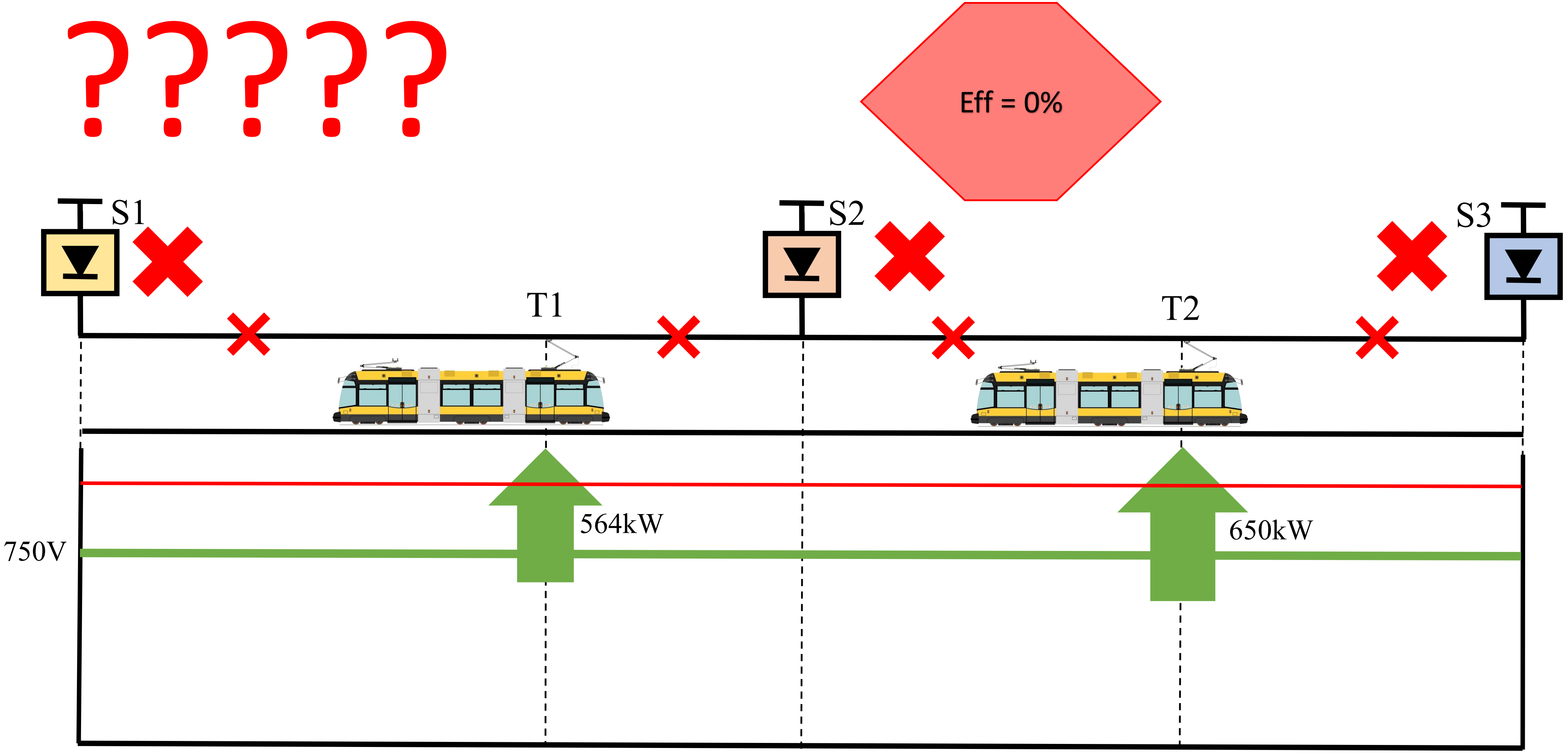
Eff = 74%



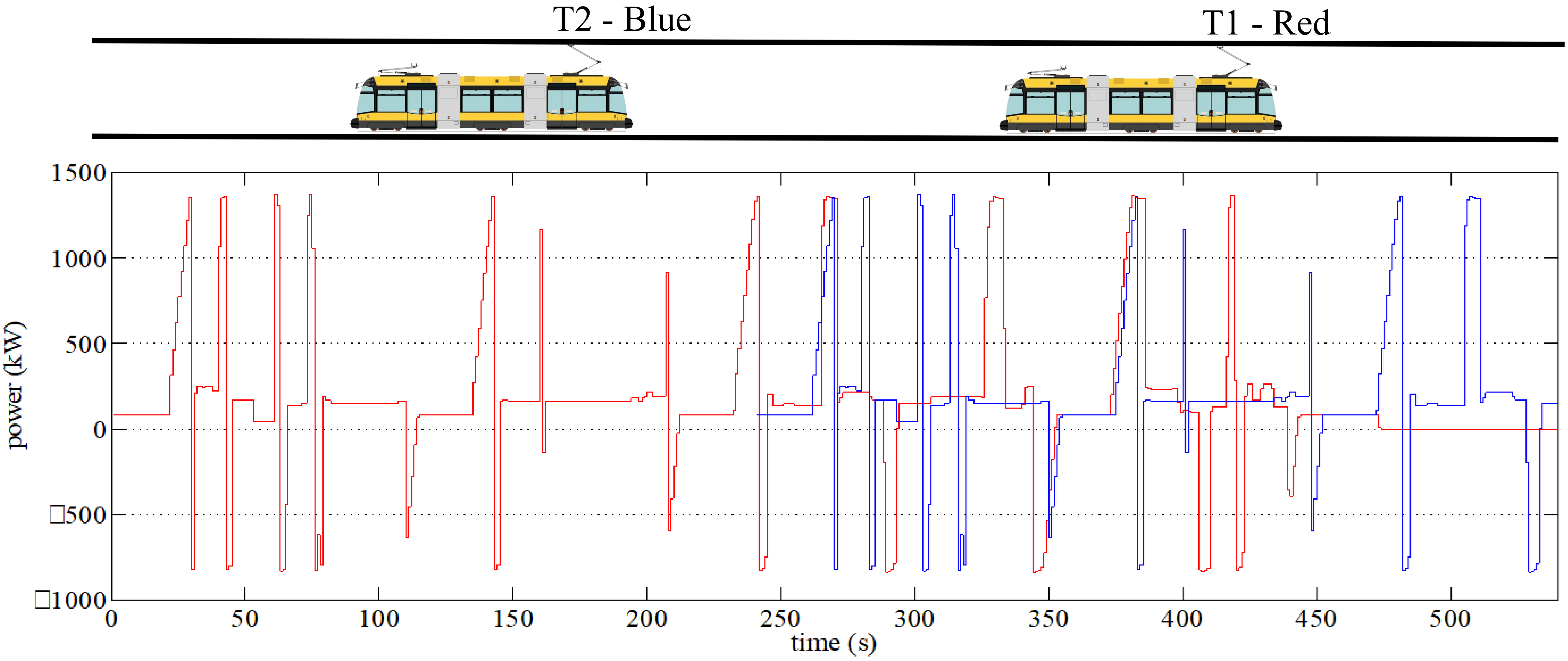
Conventional DC scenario (Case 2)



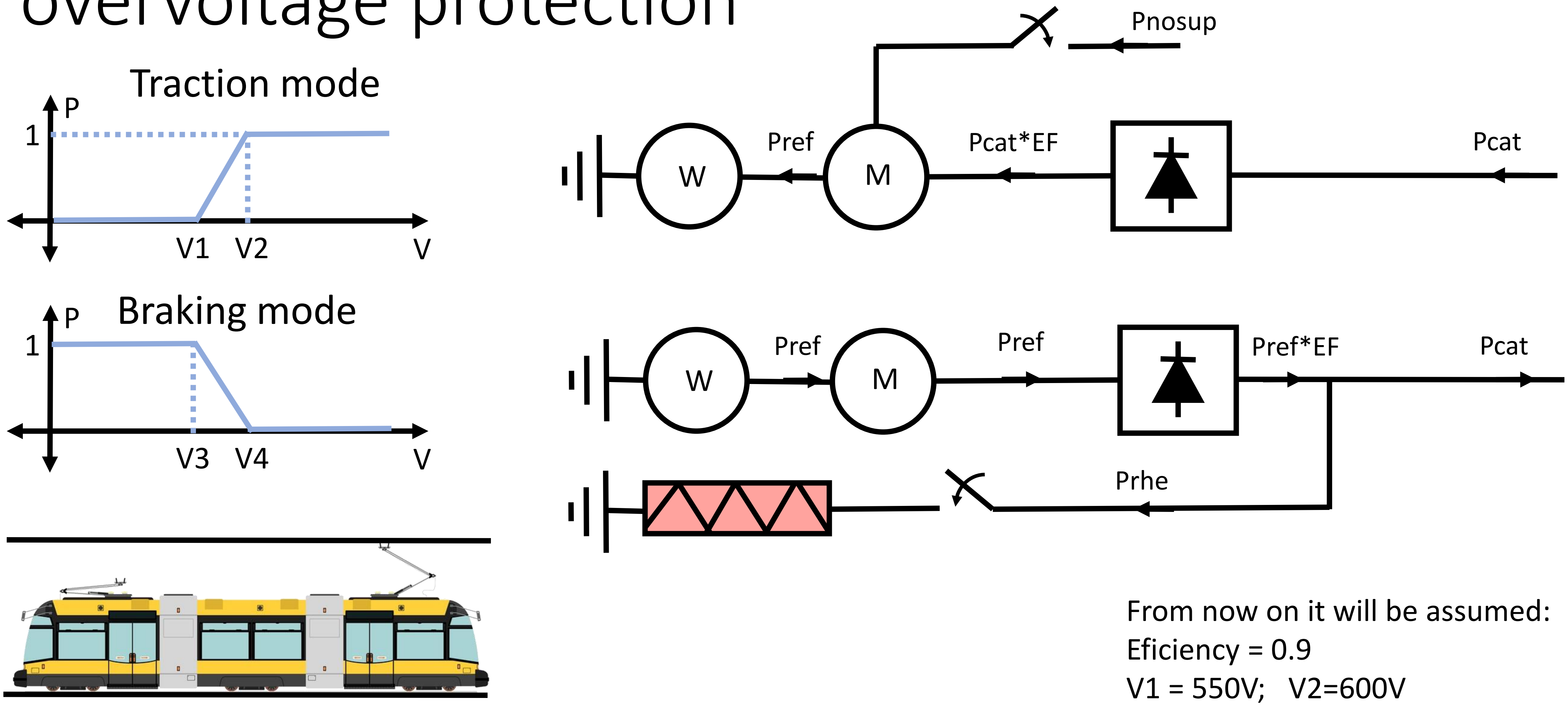
Conventional DC scenario



How often each scenario is present?

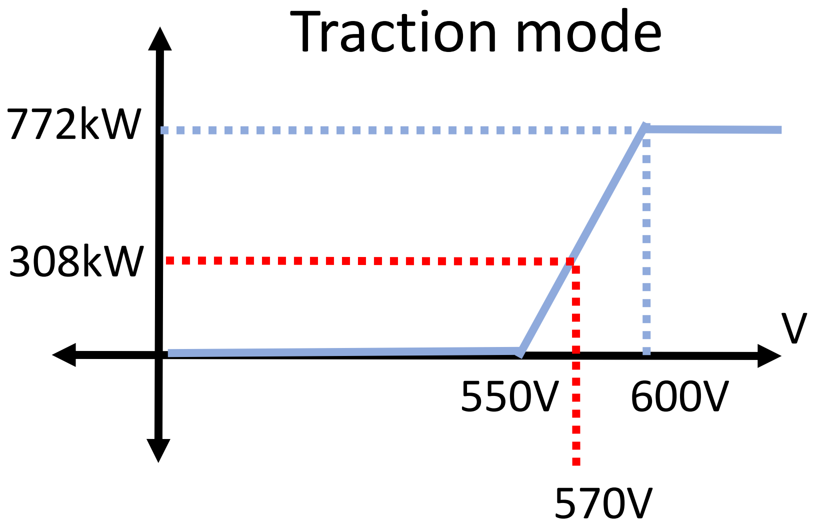


Effect of the trains overcurrent and overvoltage protection



From now on it will be assumed:
Eficiency = 0.9
V1 = 550V; V2=600V
V3 = 850V; V4=900V

Effect of the trains overcurrent protection



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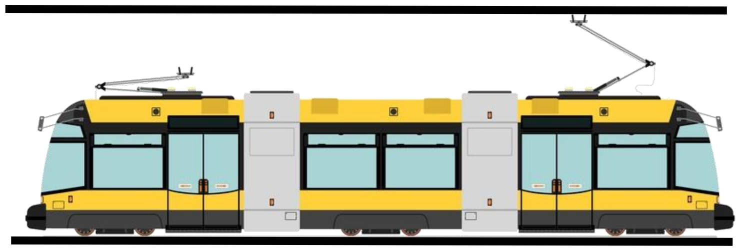
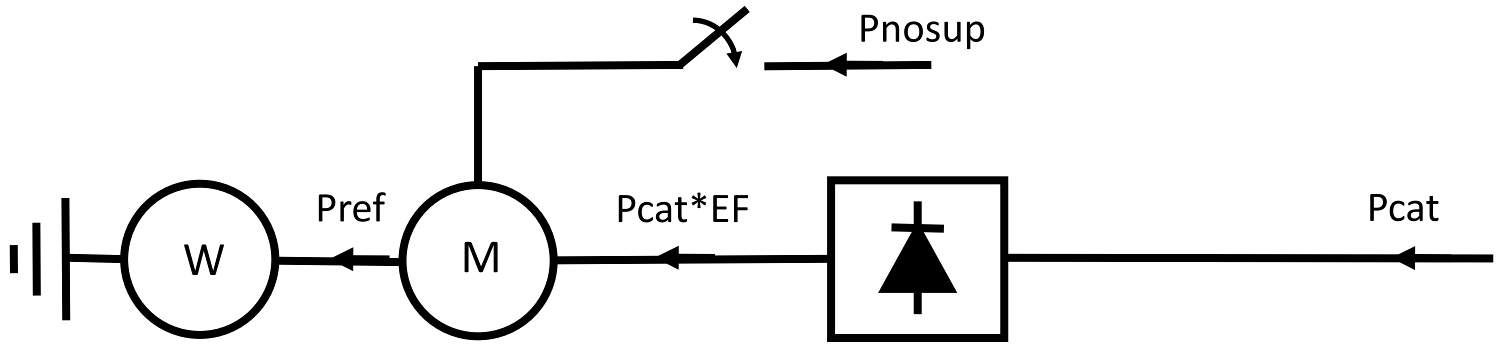
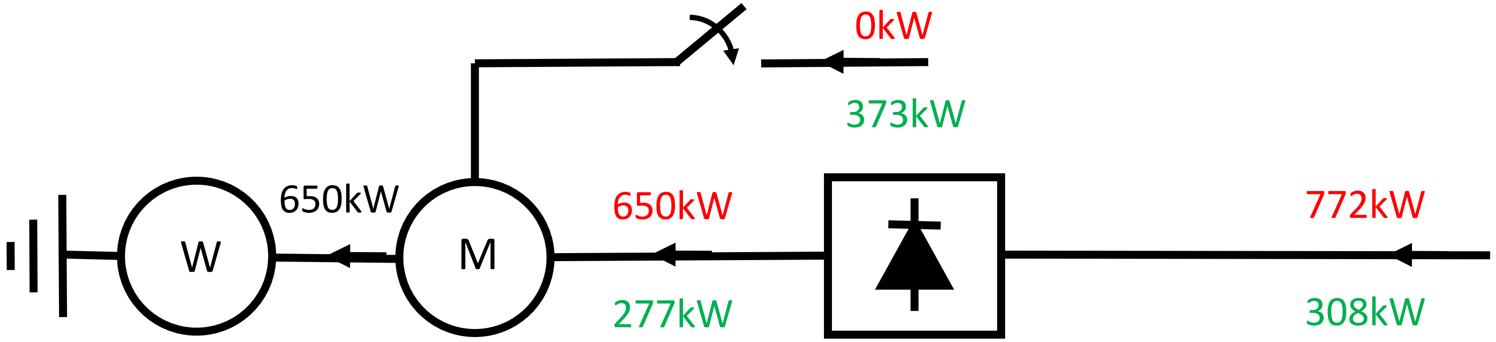




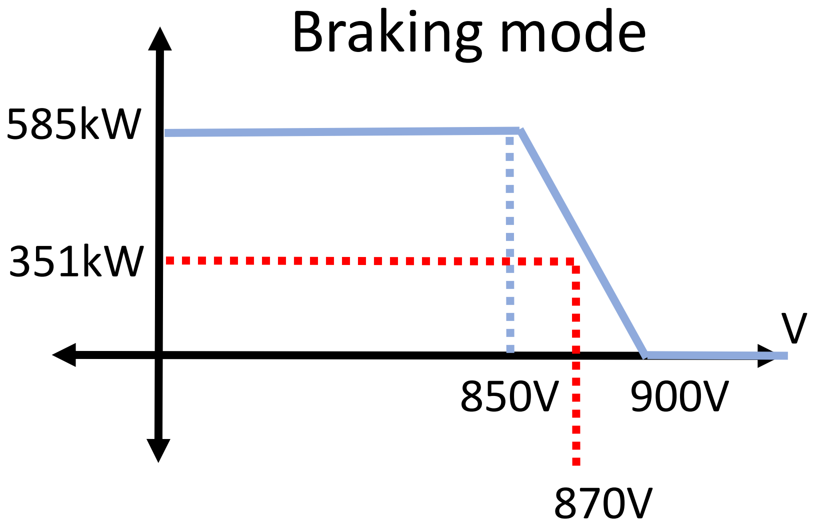
Assuming Vcat = 570V

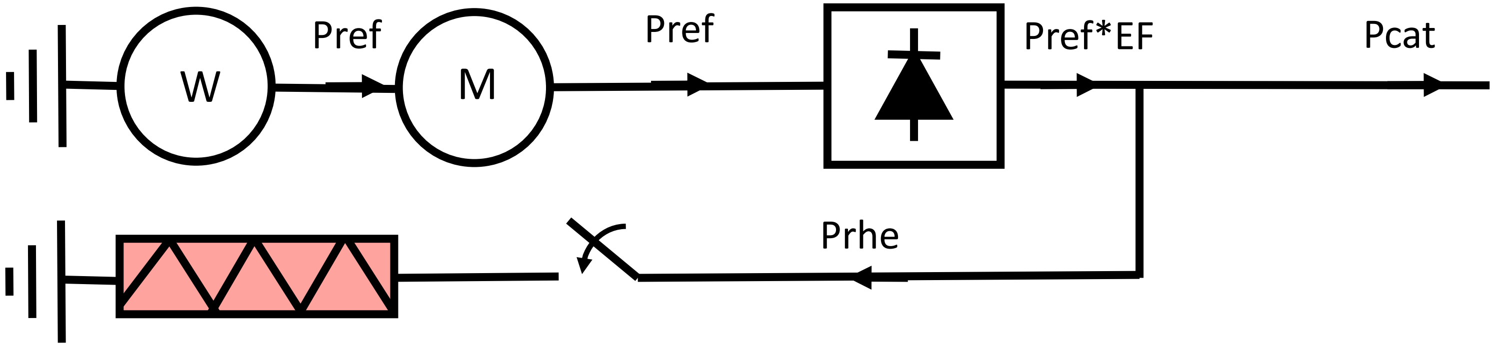
Pref = 650kW → I need from the catenary Pref/EF = 722kW

The overcurrent protection limits the power to 308kW



Effect of the trains overvoltage protection



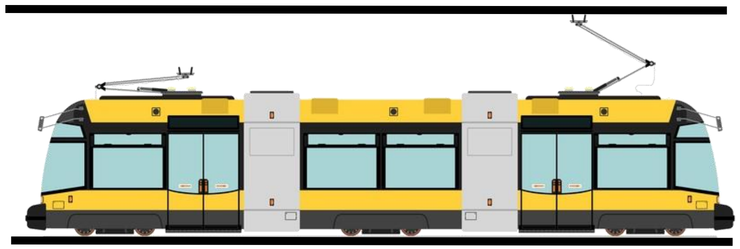


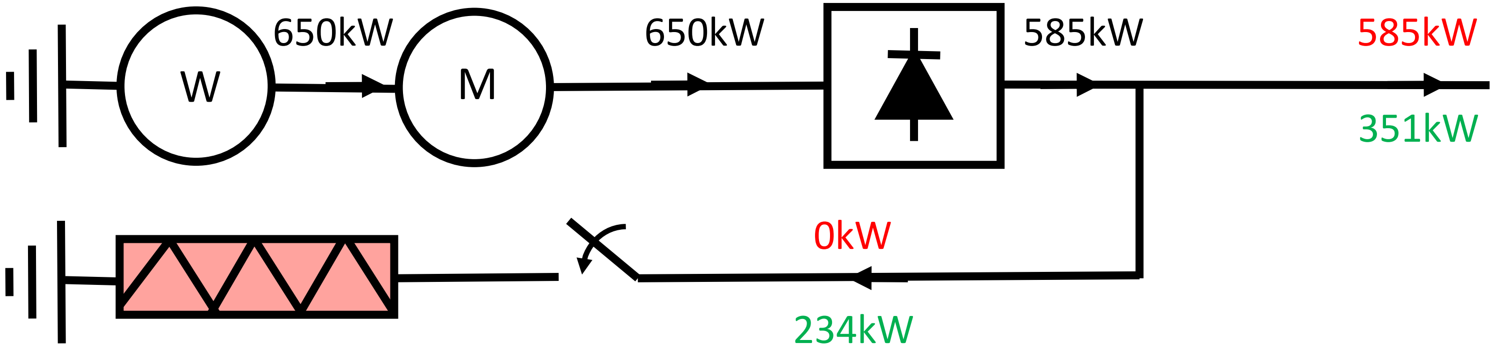
Assuming Vcat = 870V

Pref = 650kW ⟶ I would like to inject in the catenary Pref*EF= 585kW

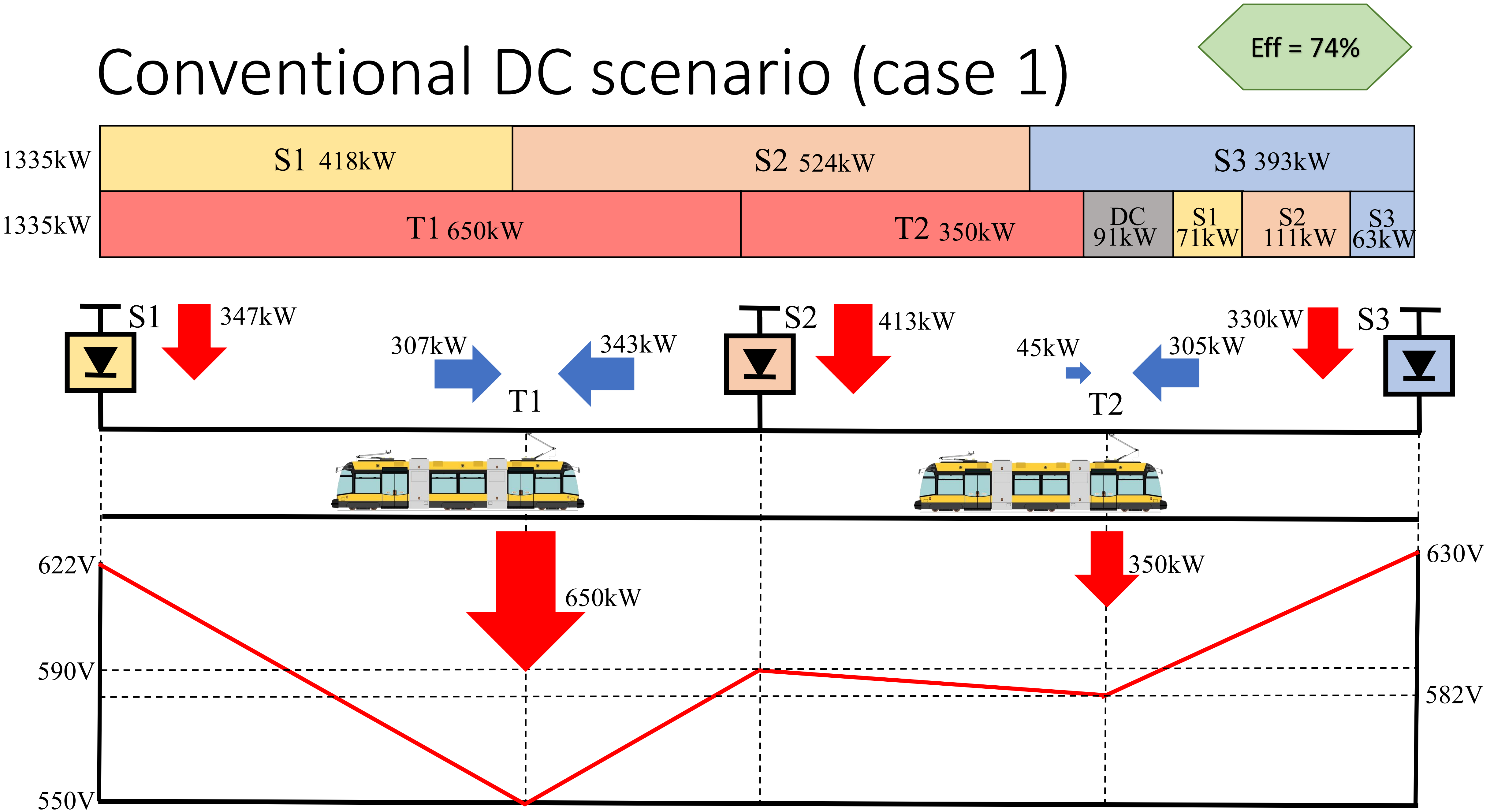
The overvoltage protection limits the power to 351kW

Efficiency = 0.9
V3 = 850V; V4=900V



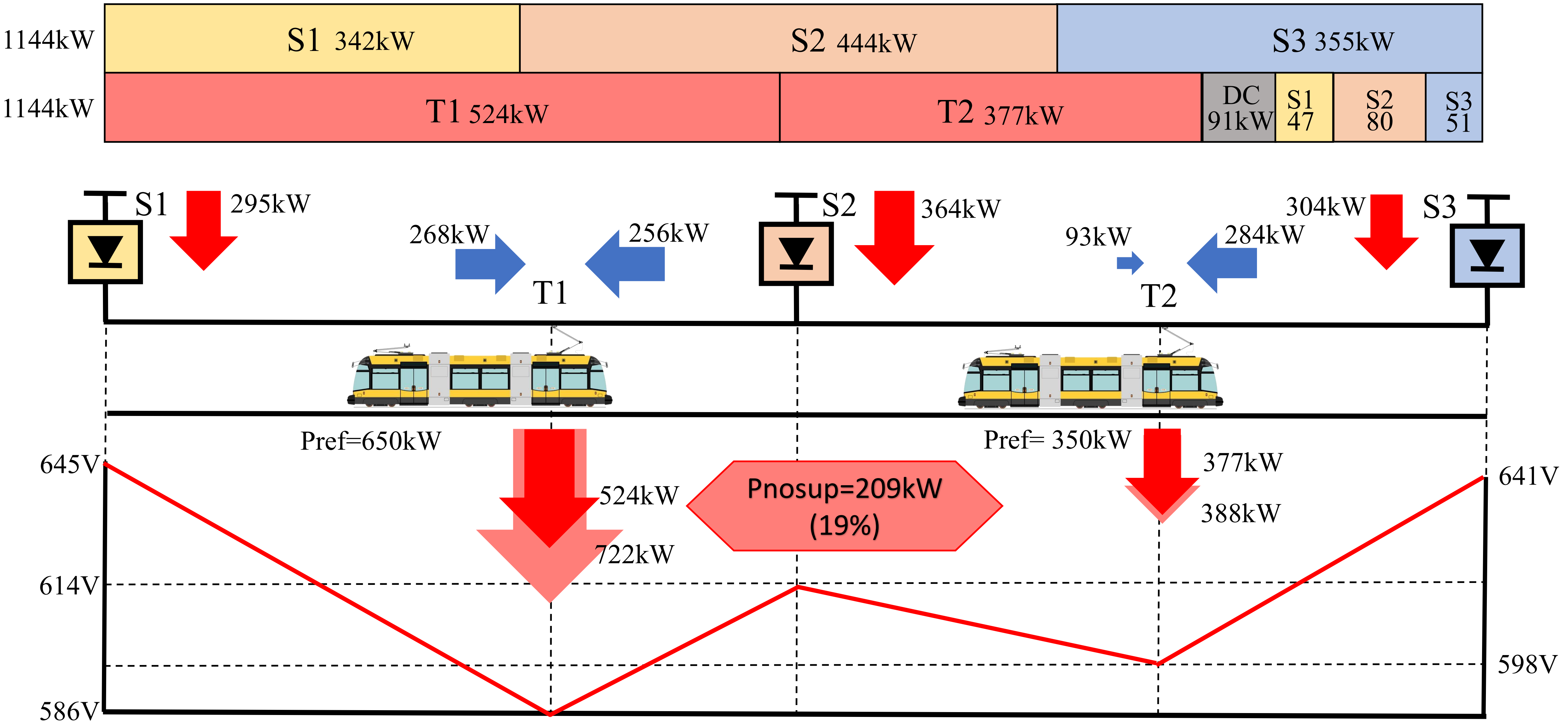


Conventional DC scenario (case 1)



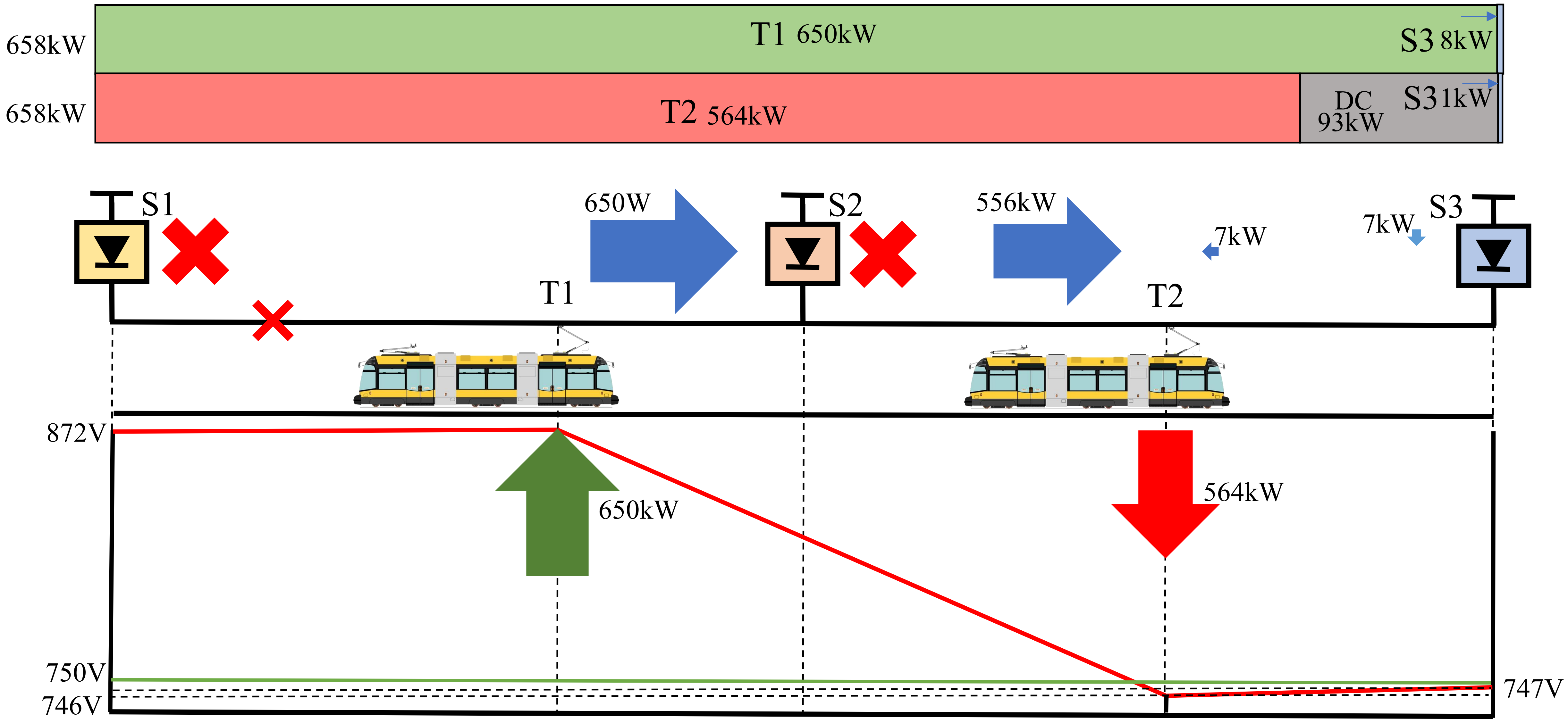
Conventional DC scenario (case 3)

Eff = 78%

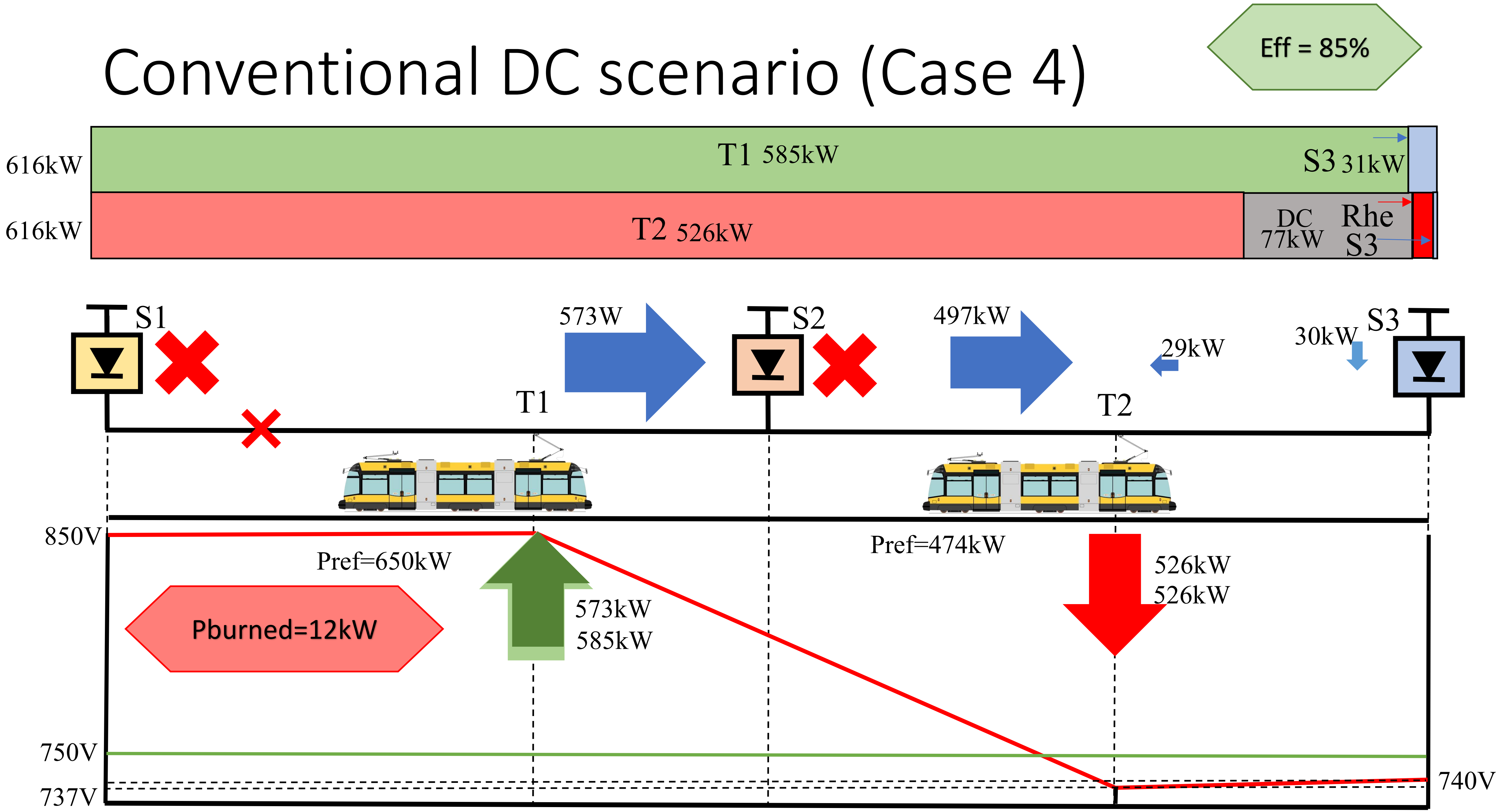


Conventional DC scenario (Case 2)

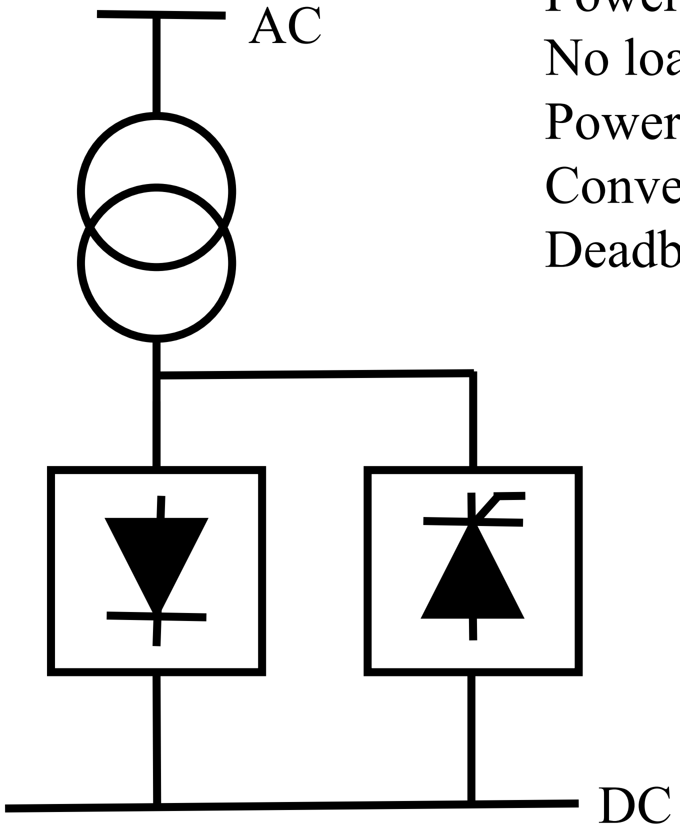
Eff = 85%



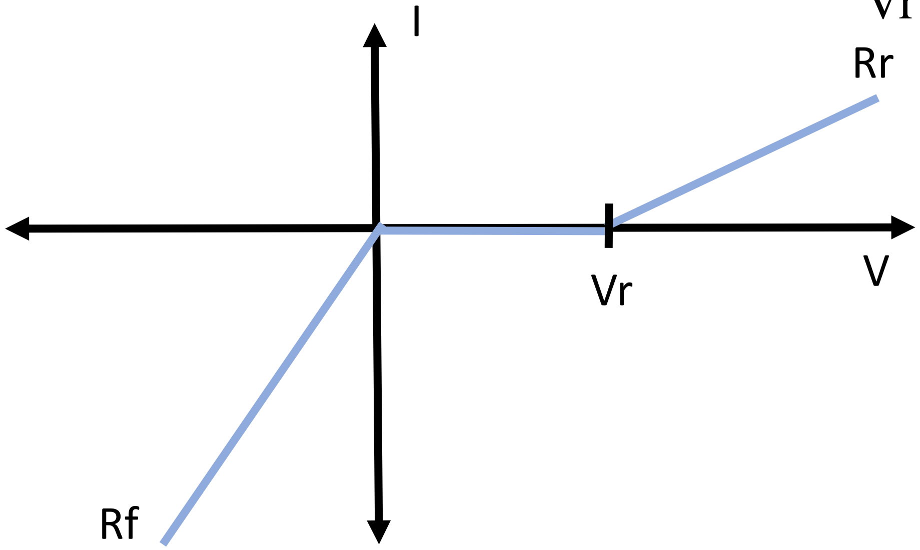
Conventional DC scenario (Case 4)



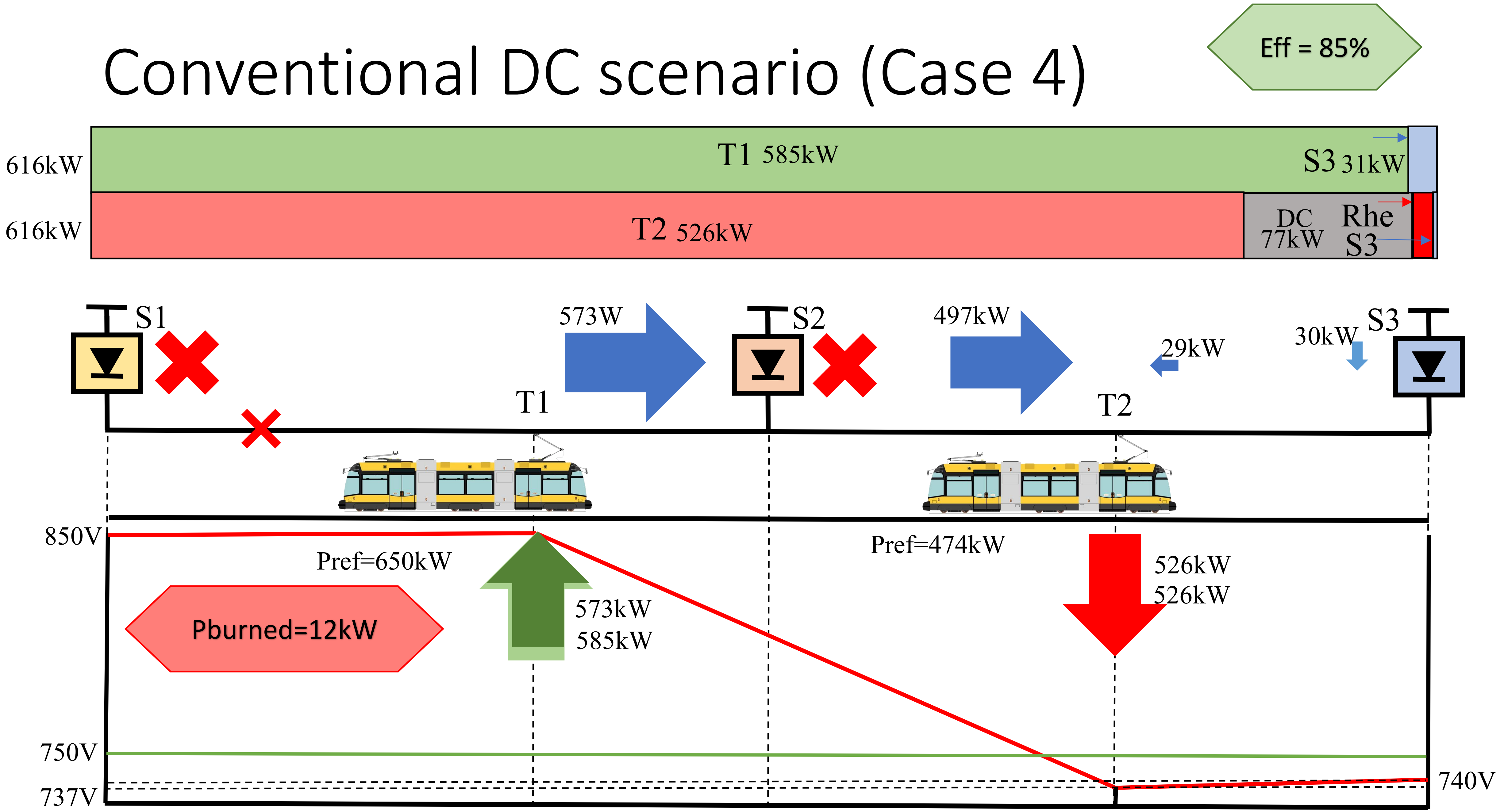
Reversible substations as a solution to increase the efficiency



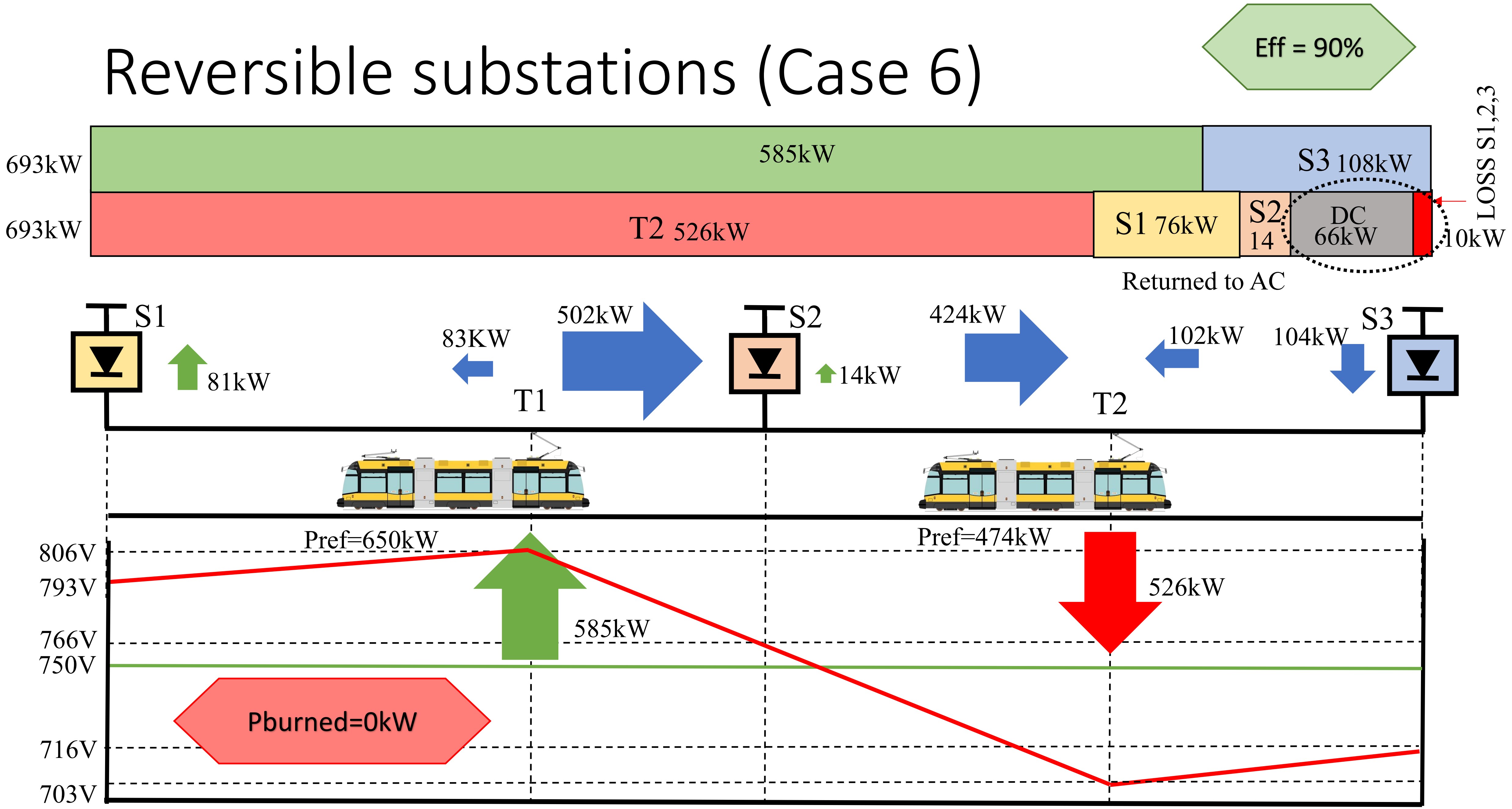
Power transformer and diode rectifier rated power: $P_r = 0{,}35$ MW
No load and rated load DC voltage: $V_0 = 750V$, $V_n = 700V$
Power transformer s.c. voltage: $V_{cc} = 8\%$
Converter rated power: $Pr = 0{,}175$ MW
Deadband: Vr = 10V

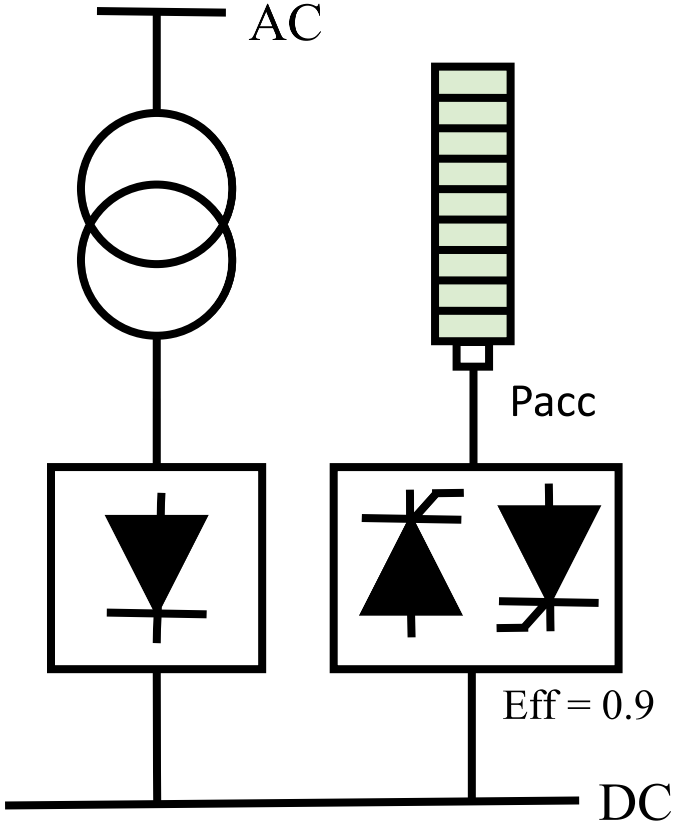


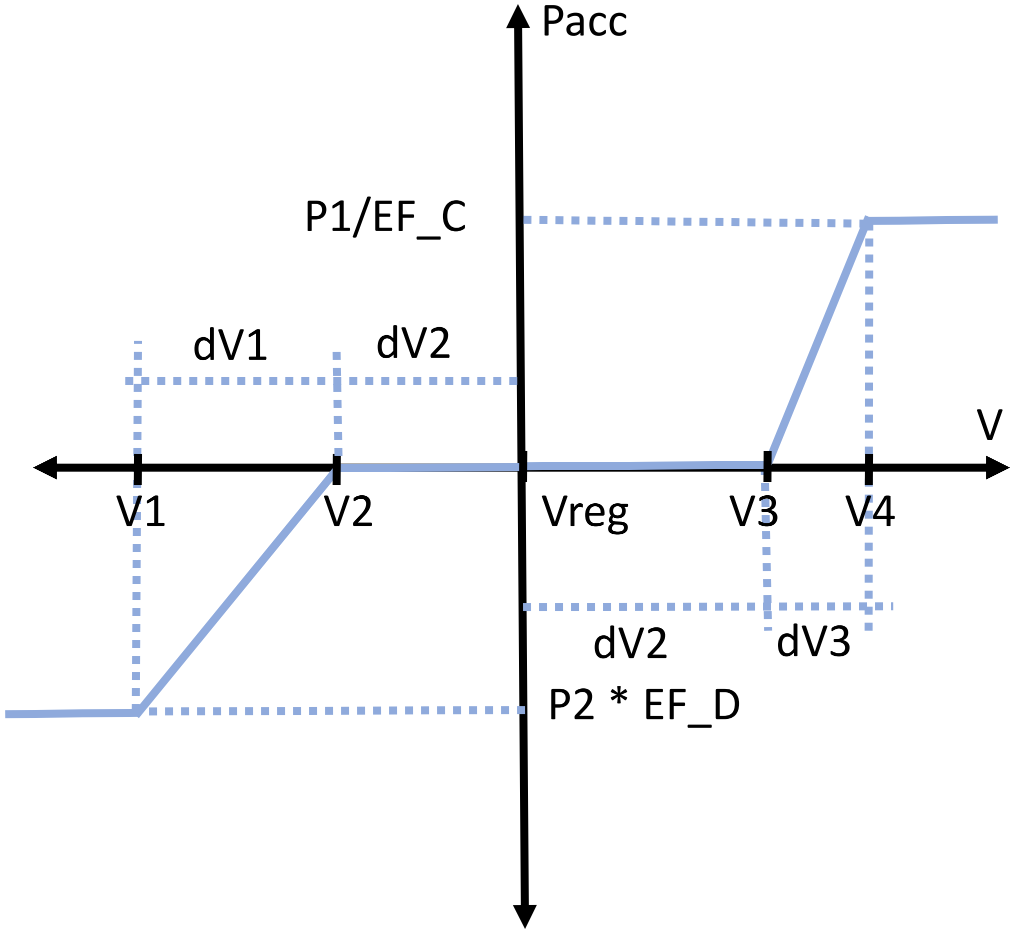
Conventional DC scenario (Case 4)



Reversible substations (Case 6)

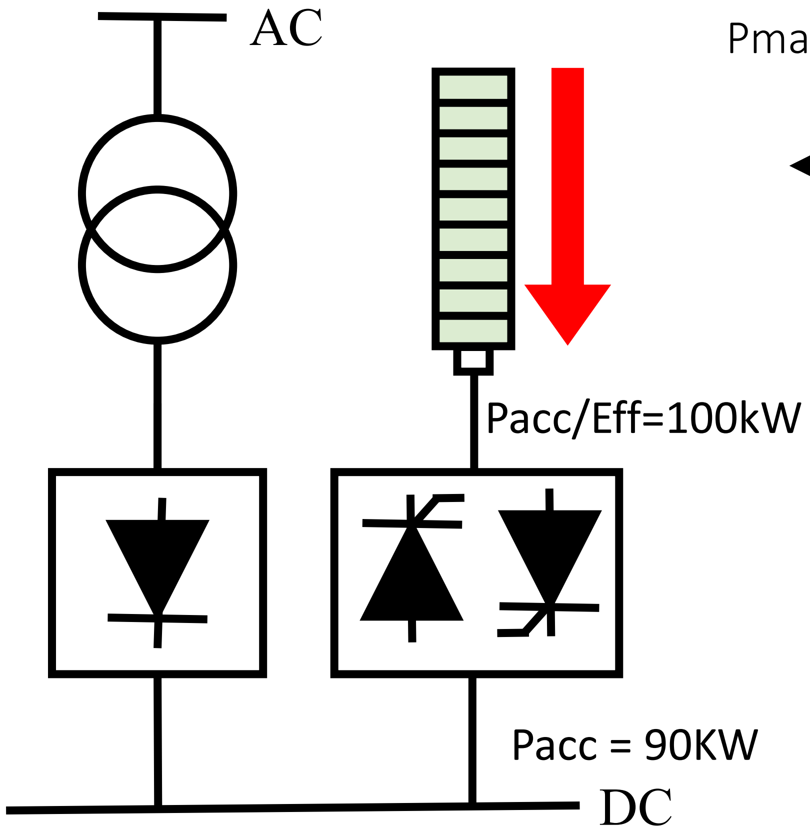


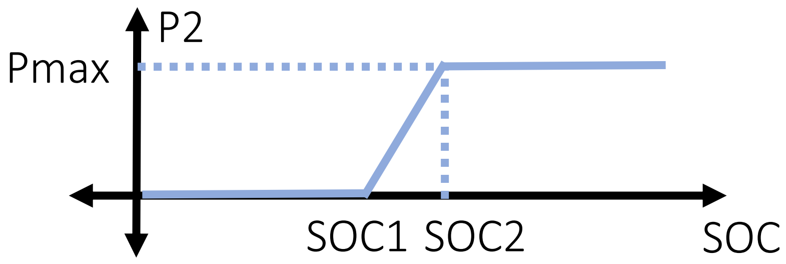


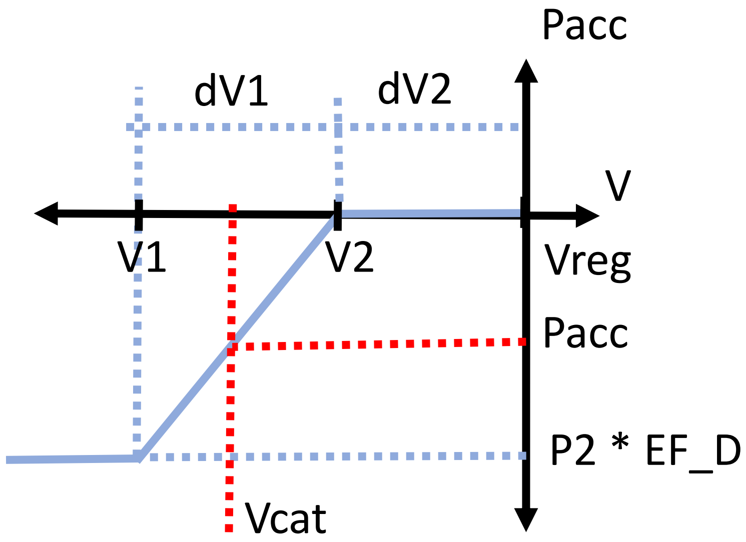


Vreg=750V, dV1 = dV2 = dV3 =10V

Off-board accumulation as a solution to increase the efficiency (Discharging mode)







SOC1 = 5%
SOC2 = 10%
Pmax = 200kW
Emax = 50kWh

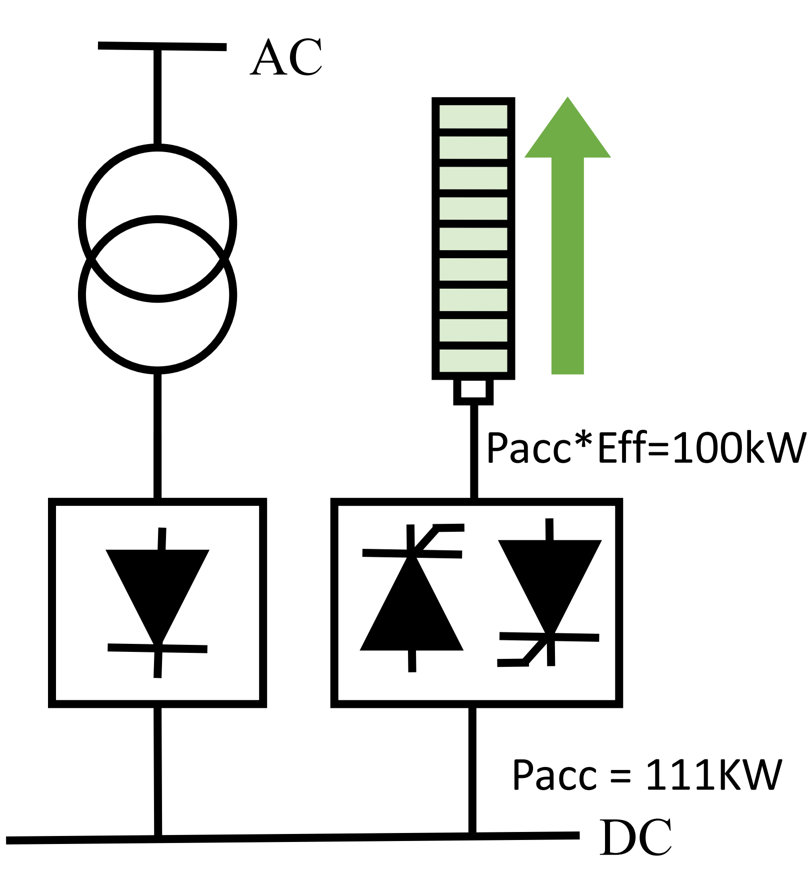
Vreg = 750V
dV1 = 10V
dV2 = 10V
Eff = 90%

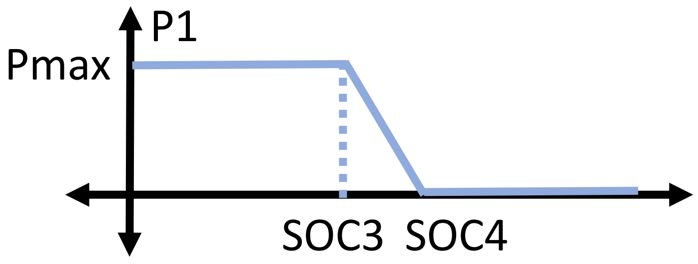
Assuming Vcat = 735V and SOC =50%

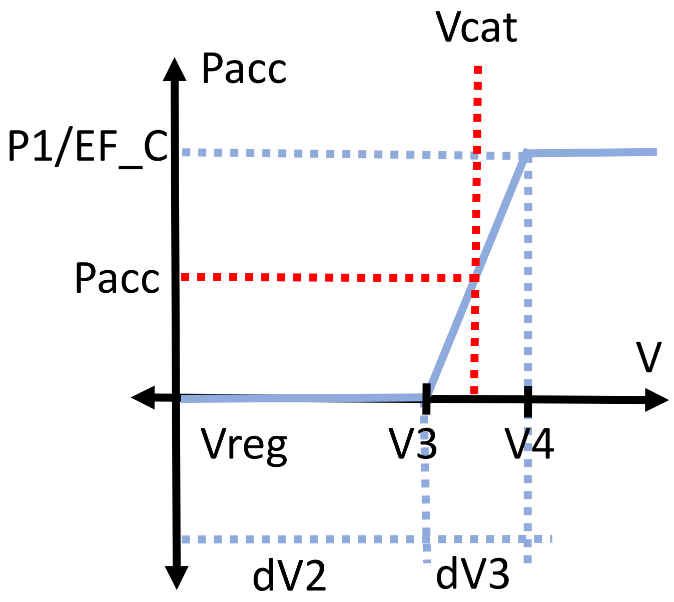
SOC =50% $\longrightarrow$ P2 = Pmax = 200kW

Vcat =735V $\longrightarrow$ Pacc = 90 kW

Off-board accumulation as a solution to increase the efficiency (Charging mode)







SOC3 = 90%
SOC4 = 95%
Pmax = 200kW
Emax = 50kWh

Vreg = 750V
dV2 = 10V
dV3 = 10V
Eff = 90%

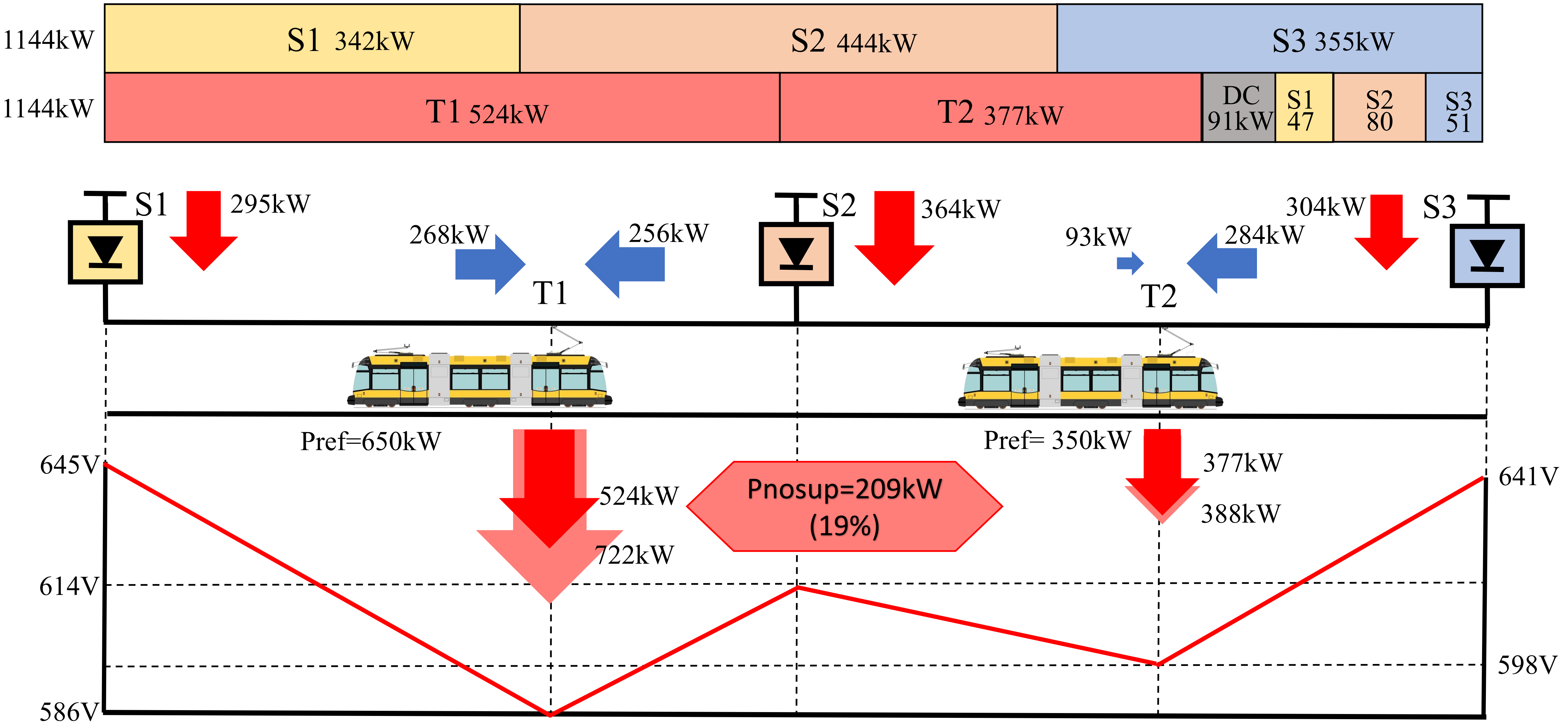
Assuming Vcat = 765V and SOC =50%

SOC =50% $\longrightarrow$ P1 = Pmax = 200kW

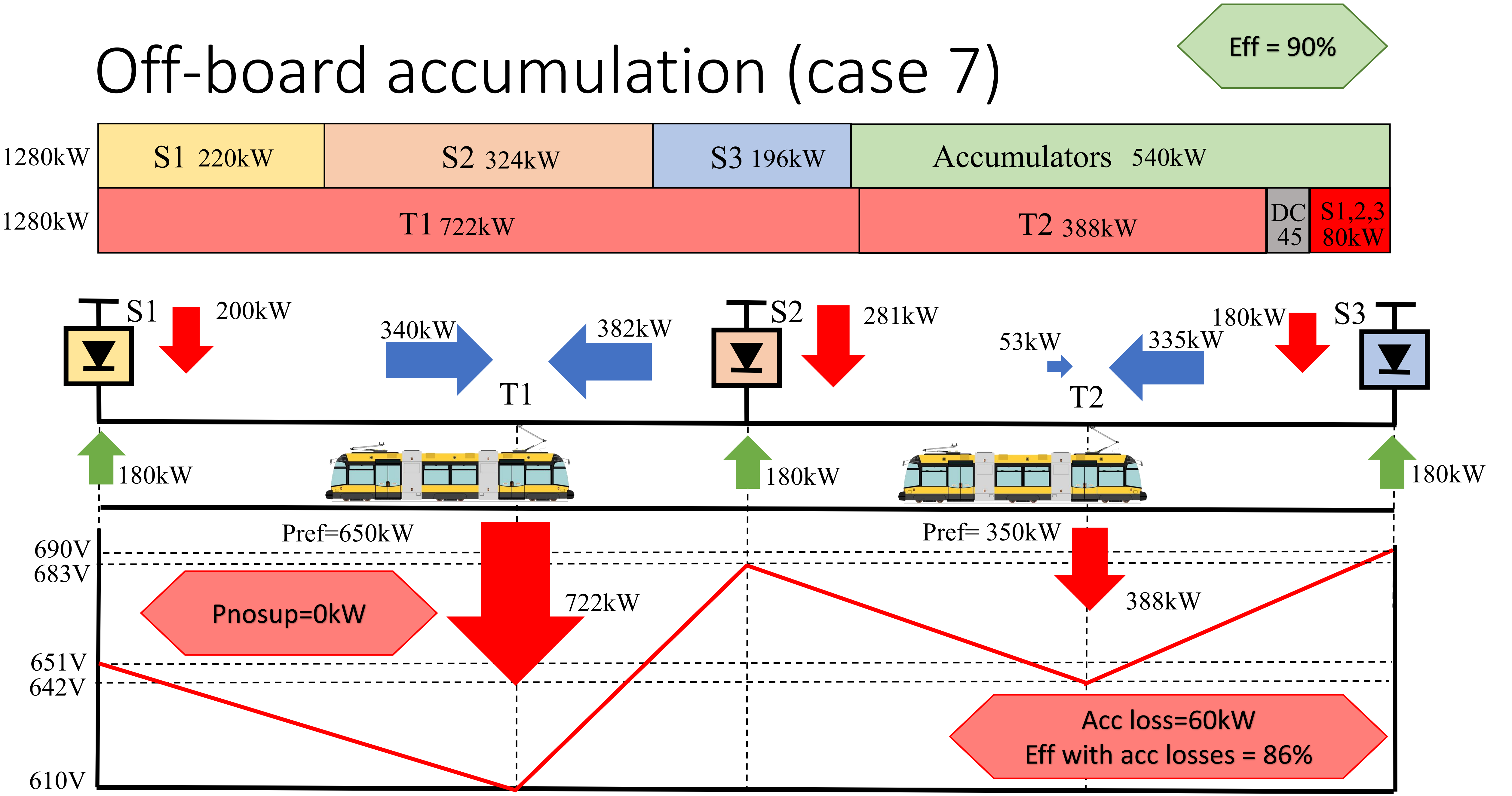
Vcat =765V $\longrightarrow$ Pacc = 111 kW

Conventional DC base scenario (case 3)

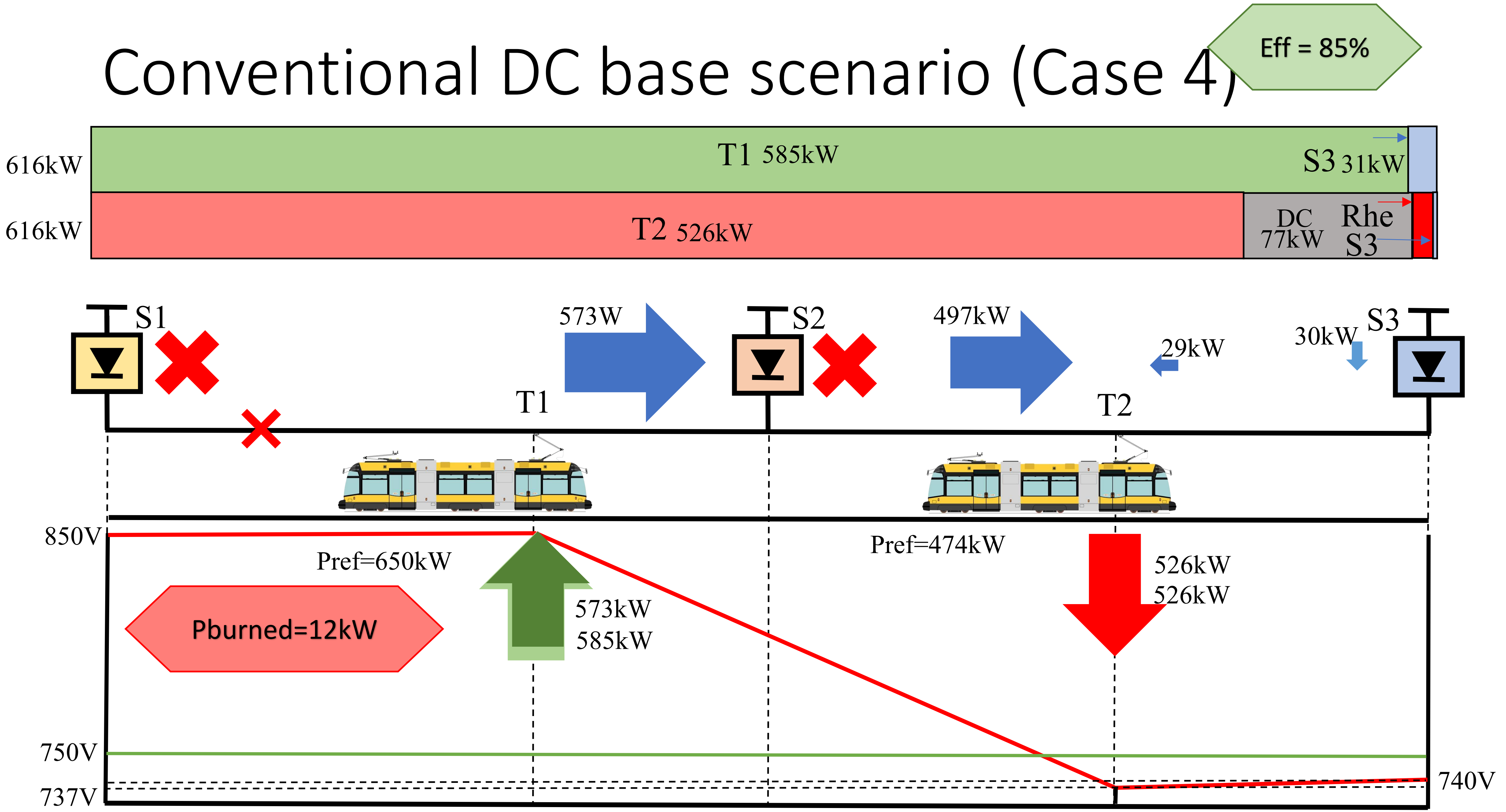
Eff = 78%



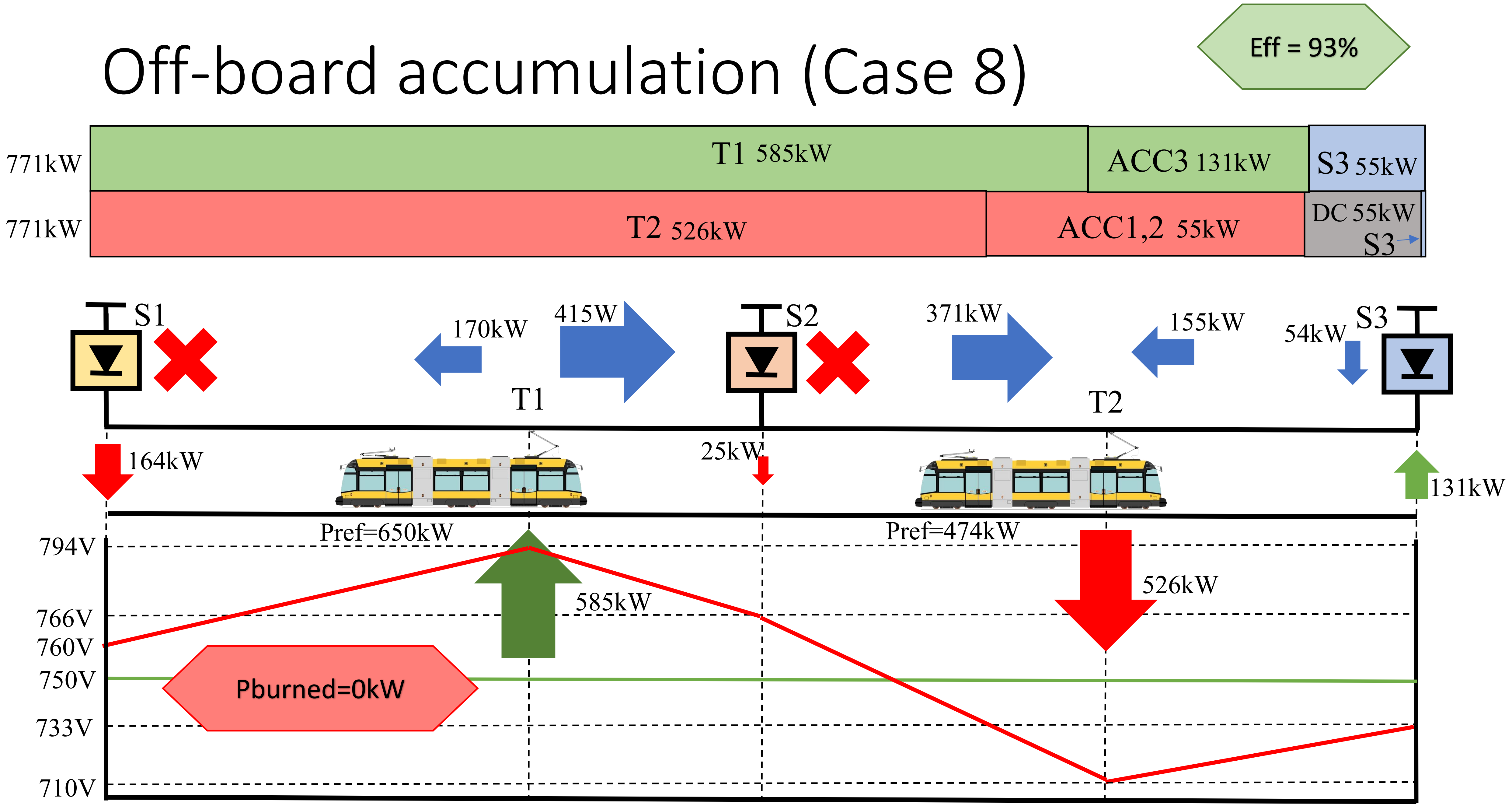
Off-board accumulation (case 7)



Conventional DC base scenario (Case 4)

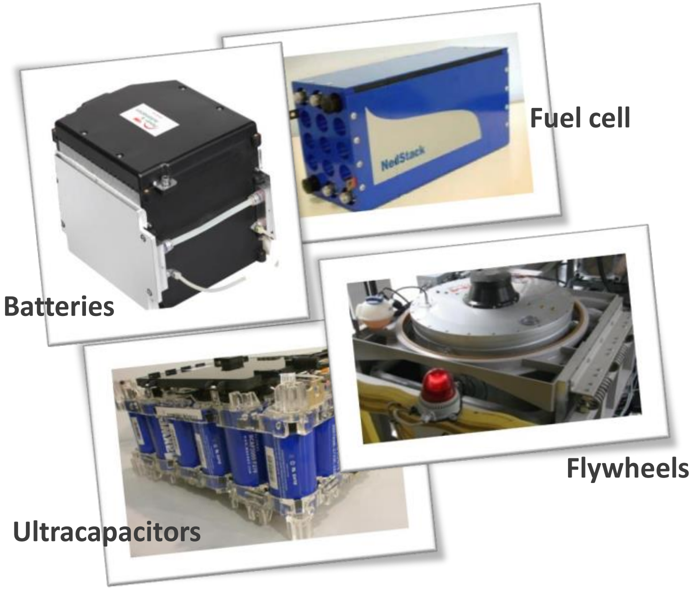


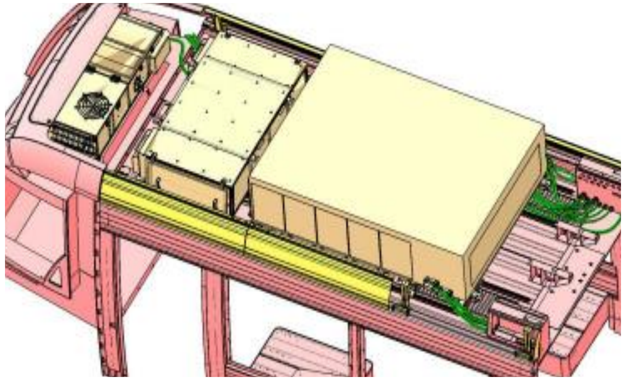
Off-board accumulation (Case 8)



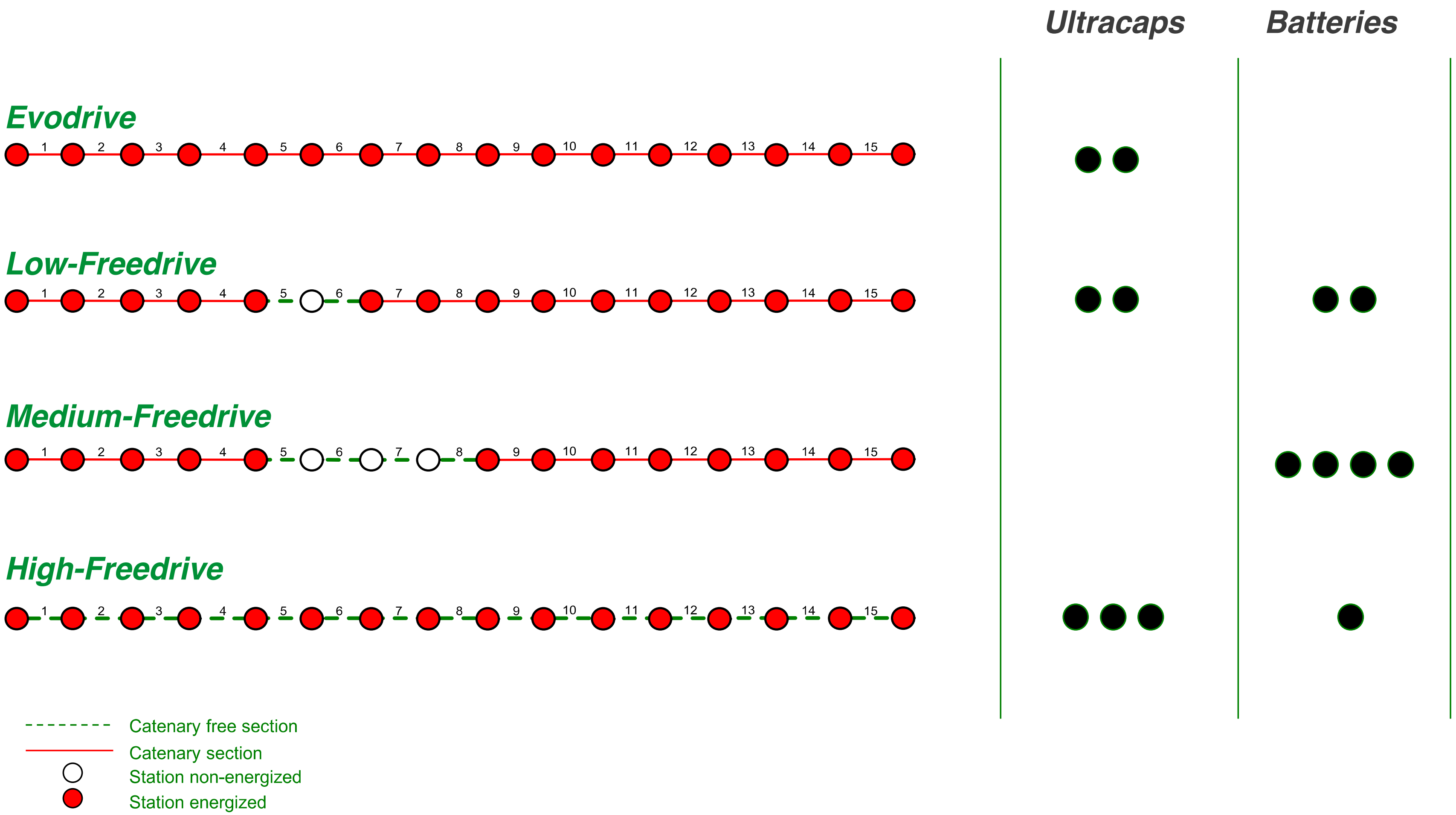
On board accumulation systems

Technologies/ Features (● Bad ● Medium ● Good)	Life Cycle Cost	Energy Density	Power	Fast Charging	Availability	Safety	Maturity
Fuel-Cell (Hydr.)	Low	High	Med.	Yes	Med.	Low	Low
Batteries	Med.	High	Low	No	High	High	High
Flywheel	Med.	Low	High	Yes	Med.	Med.	High
Supercapacitors	Med.	Med.	High	Yes	High	High	High



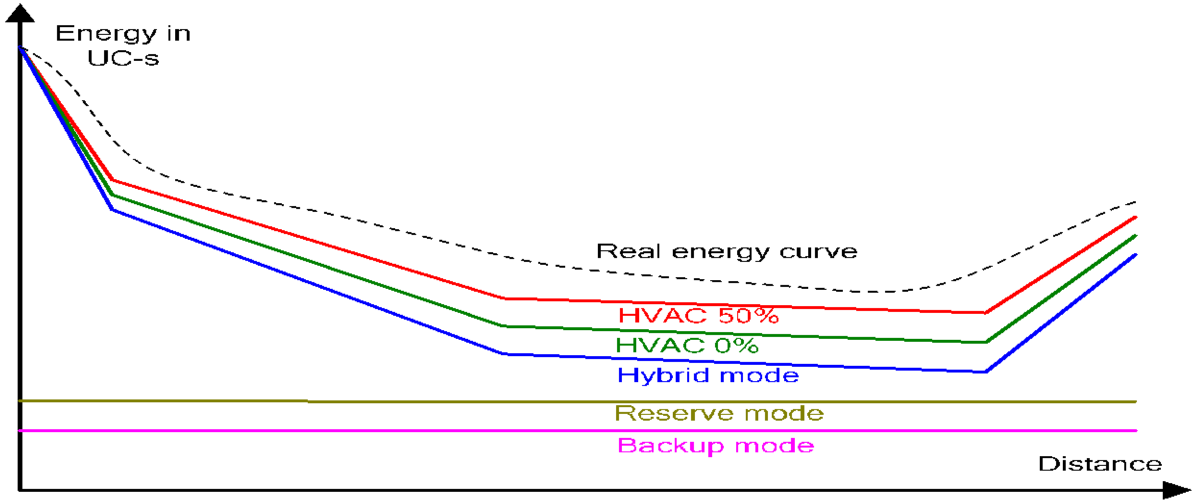


Hybridization of On-board accumulation systems



On board accumulation systems – Kaohsiung example

- 100% Catenary free
- 5 module version
  (tare 49 tones, max. mass 69 tones)
- 48 seats, 228 people.
- 750V, 400kW rated power (800kW max)
- Total energy ultracapacitors (7stacks): 4.1kWh (8,2kWh/train)
- Total energy ultracapacitors (7stacks): 15kWh (30kWh/train)
- Actions in abnormal conditions:
  - Preventive actions: do not modify the train performance.
    - Reduce the cooling 50%,
    - Disconnect the cooling keeping the ventilation
    - Activate the hybrid traction mode
  - Corrective actions: 2 kind, they do affect the train performance.
    - Decrease train performance gradually
    - Back-up mode (speed limited to 5km/h)



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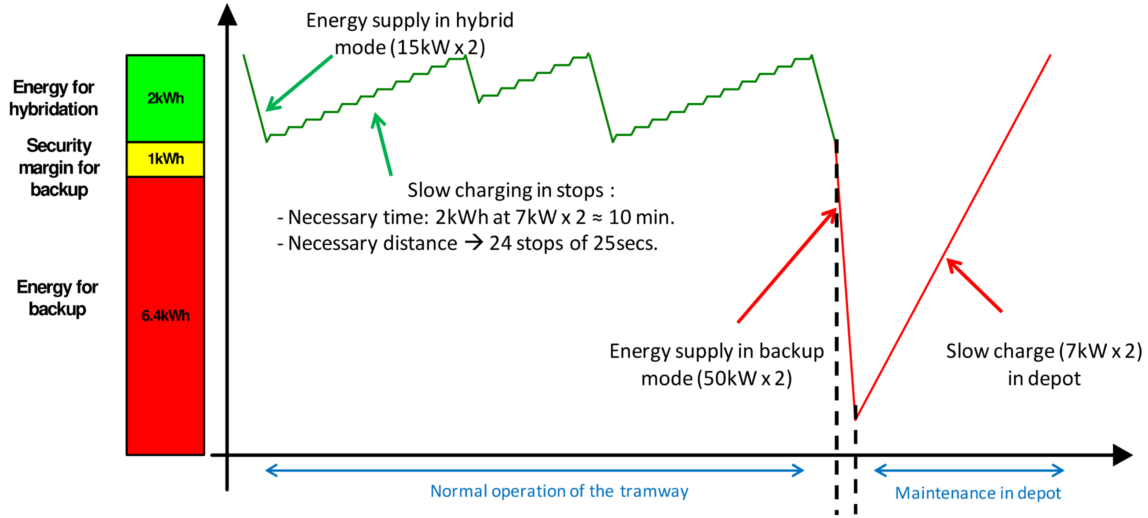
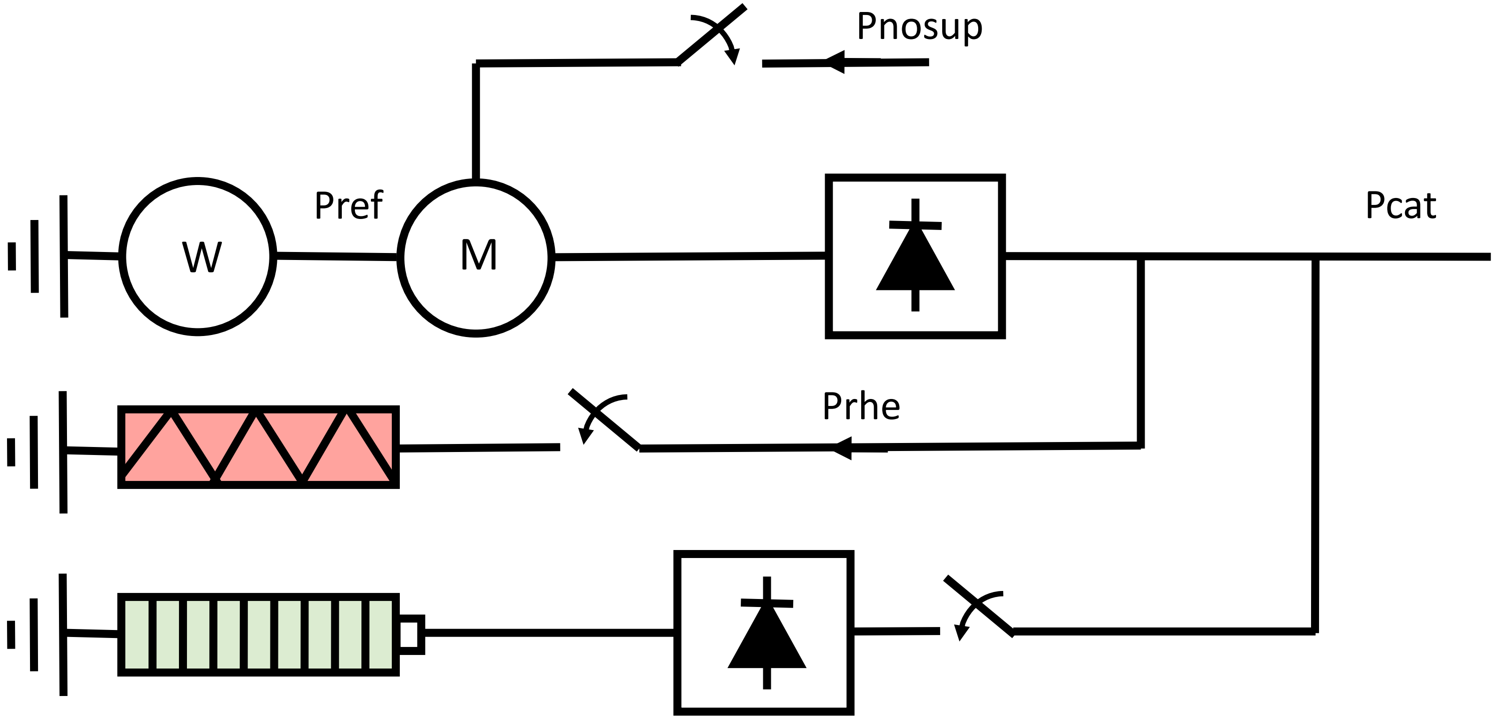


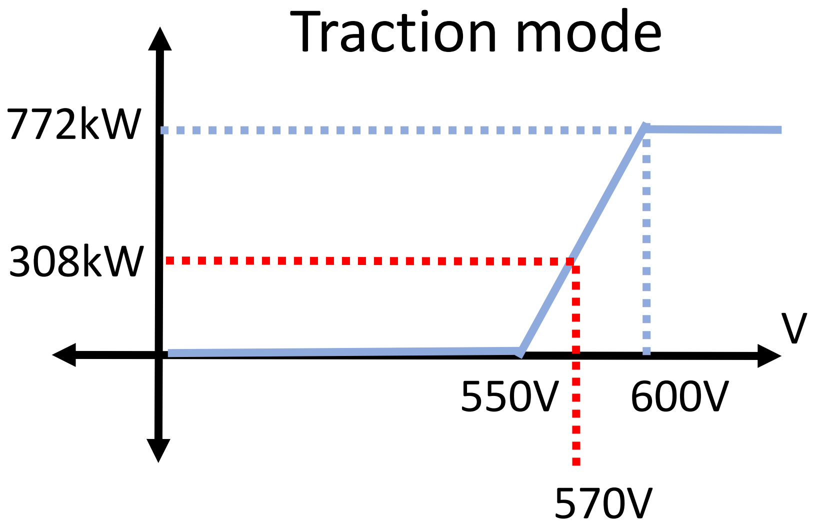
Charging stations

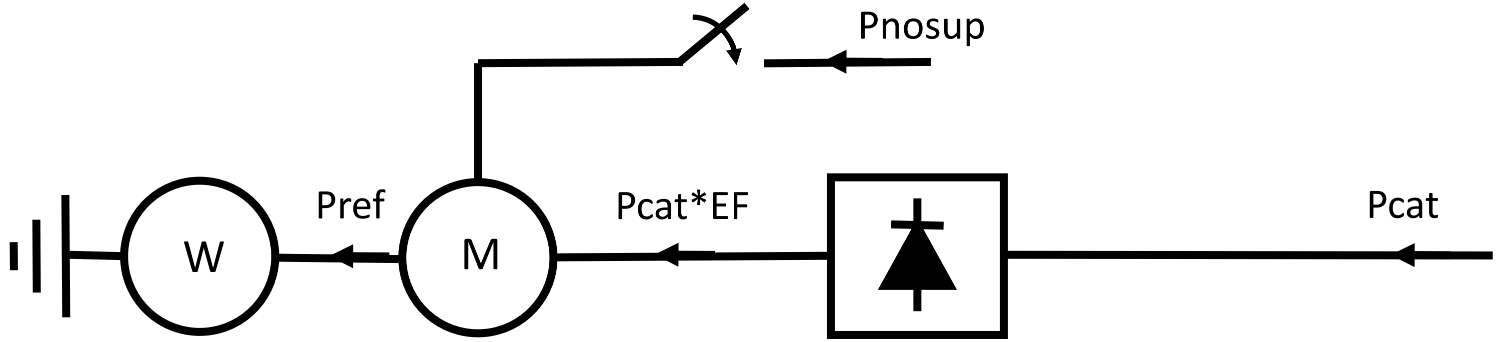
On-board accumulation as a solution to increase the efficiency

- The target at each instant is to make Pcat=0.
- The whole system will assign priority to the accumulation
- In traction mode, it will try to extract all demanded power from the accumulator, the rest will be extracted from the catenary (if possible).
- In braking mode, it will try to inject all the regenerated power into the accumulation system, the surplus will be injected in the network if possible, if not it will be burned in the rheostatic system.
- For calculation purposes the train and the storage system as considered as a separated devices as it will be shown in the next slides.



Train in traction mode – accumulator discharging



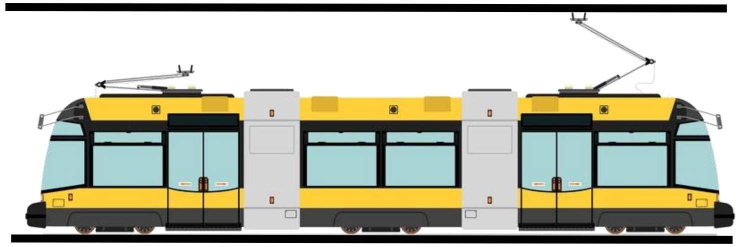


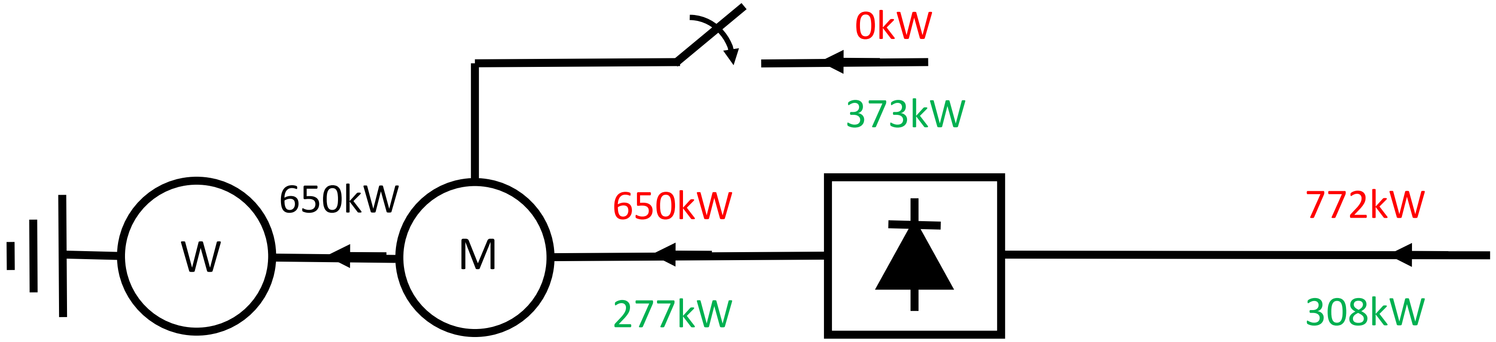
Assuming Vcat = 570V

Pref = 650kW → I need from the catenary Pref/EF = 722kW

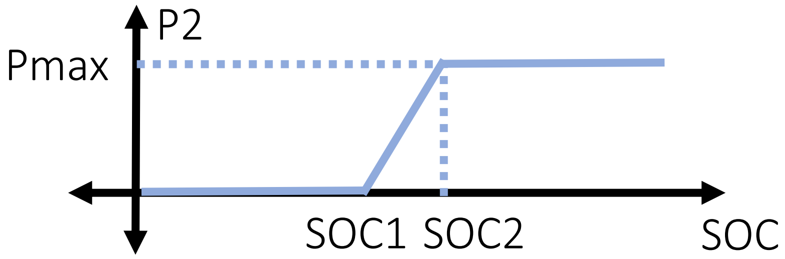
The overcurrent protection limits the power to 308kW

Efficiency = 0.9
V1 = 550V; V2=600V

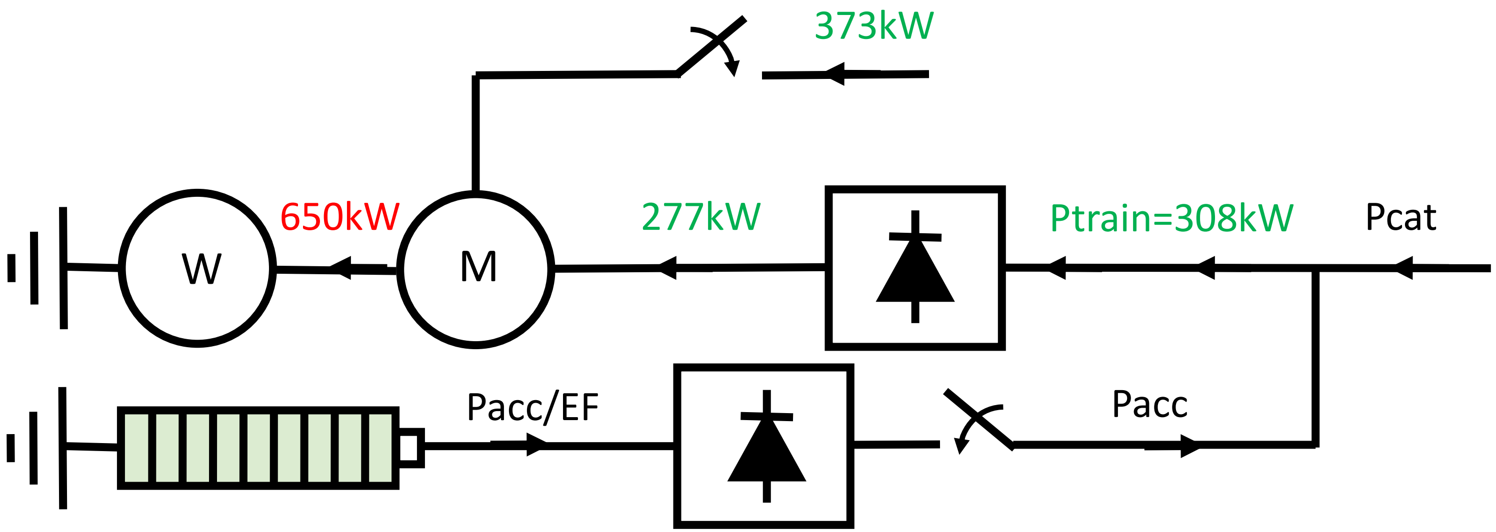




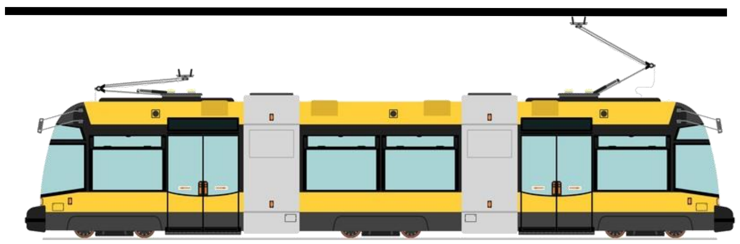
Train in traction mode – accumulator discharging



SOC1 = 5%
SOC2 = 10%
Pmax = 300kW
Emax = 20kWh
Eff = 90%



Assuming Vcat = 570V and SOC =50%

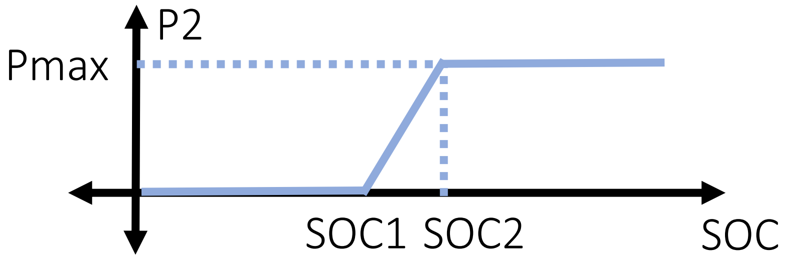


SOC =50% ⟶ P2 = Pmax = 300kW ⟶ Pacc_available = Pmax*Eff= 270kW

Pacc = min (Pacc_available, Ptrain) = min(270,308) = 270kW

Pcat = Ptrain-Pacc =308 – 270 = 38kW

Train in traction mode – accumulator discharging



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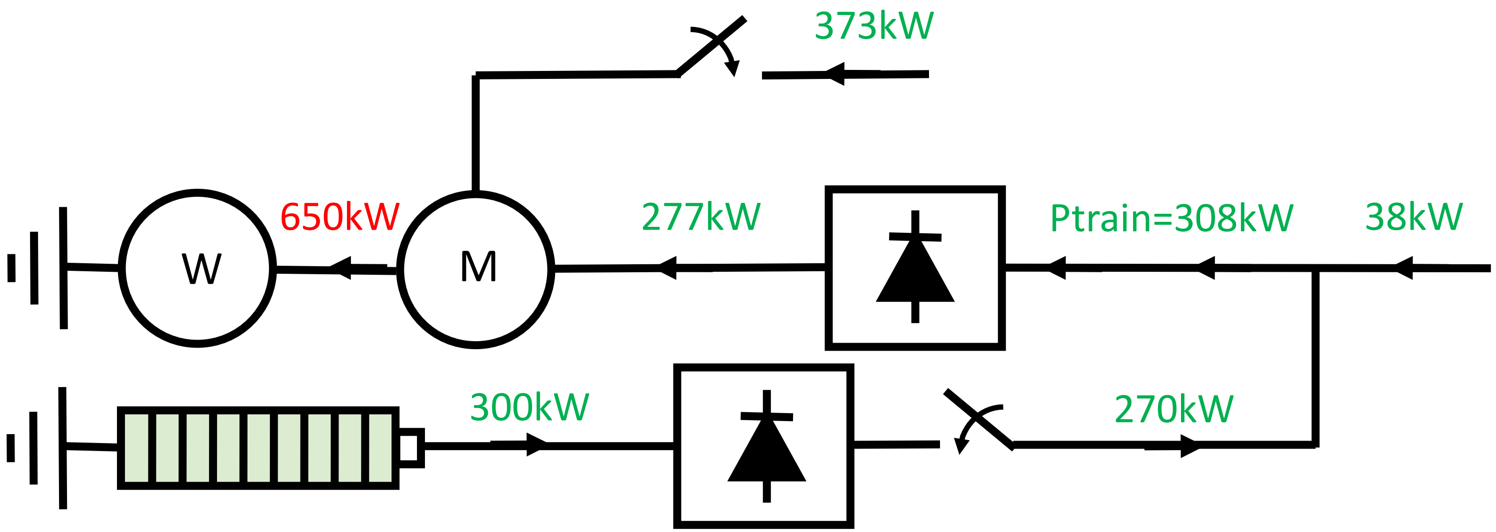
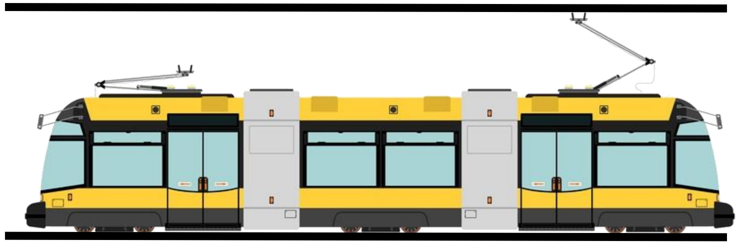


Assuming Vcat = 570V and SOC =50%

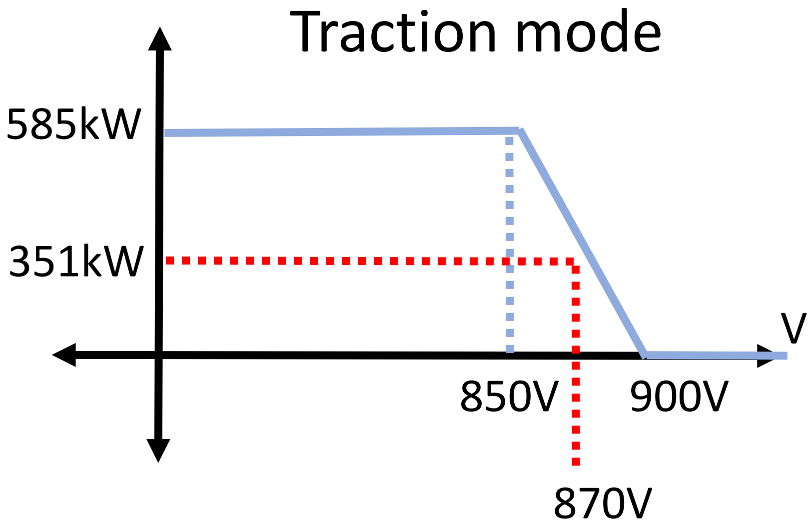


SOC =50% ⟶ P2 = Pmax = 300kW ⟶ Pacc_available = Pmax*Eff= 270kW

Pacc = min (Pacc_available, Ptrain) = min(270,308) = 270kW

Pcat = Ptrain-Pacc =308 – 270 = 38kW

Train in braking mode – accumulator charging



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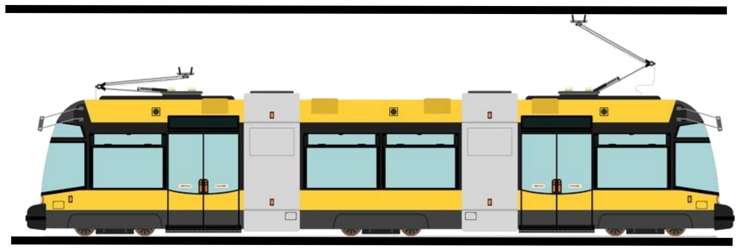

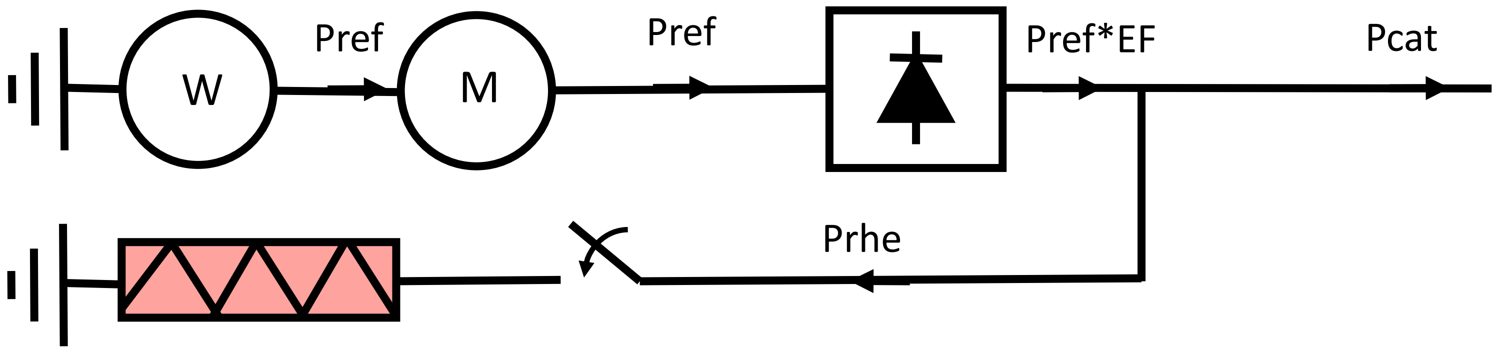

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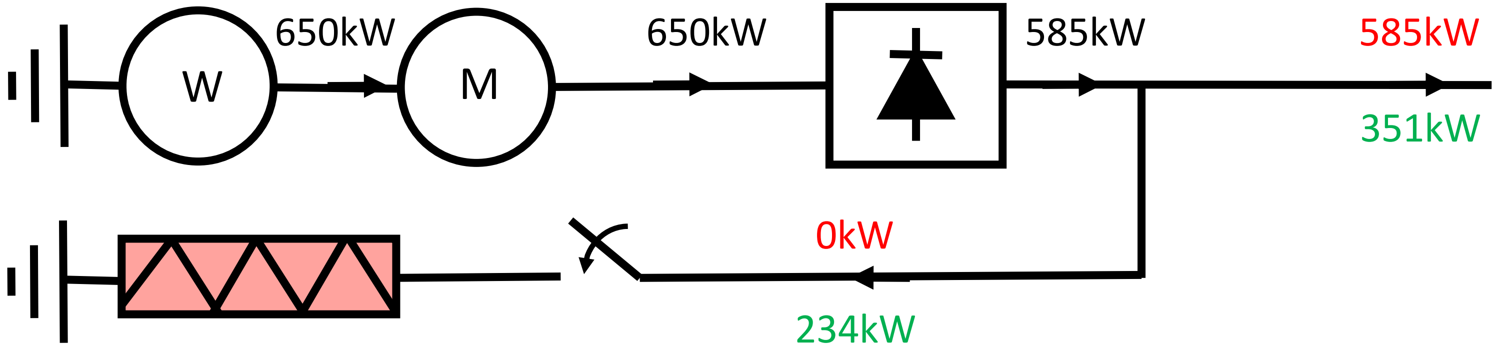
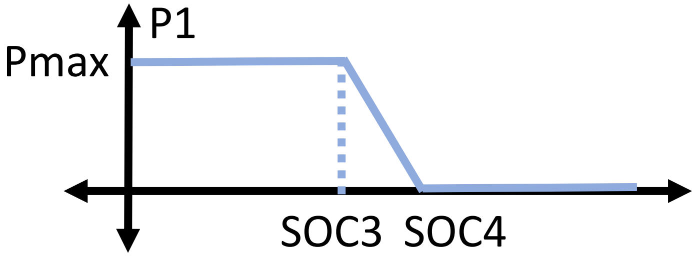
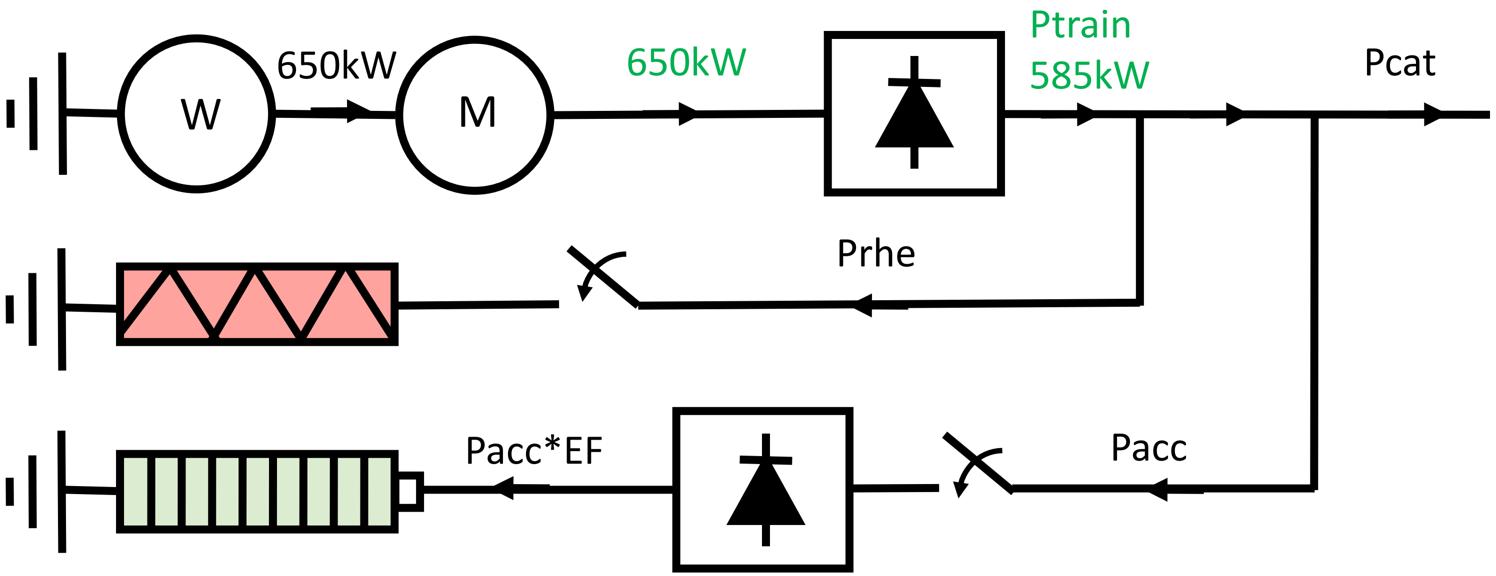
Pref = 650kW ⟶ I would like to inject in the catenary Pref*EF= 585kW

The overvoltage protection limits the power to 351kW



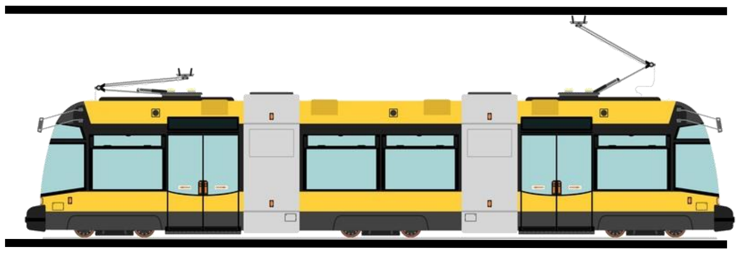
Train in braking mode – accumulator charging





SOC1 = 90%
SOC2 = 95%
Pmax = 300kW
Emax = 20kWh
Eff = 90%
Pcat_max = 351kW

Assuming Vcat = 870V and SOC =50%

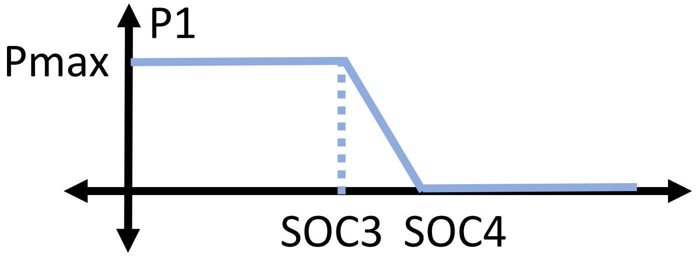


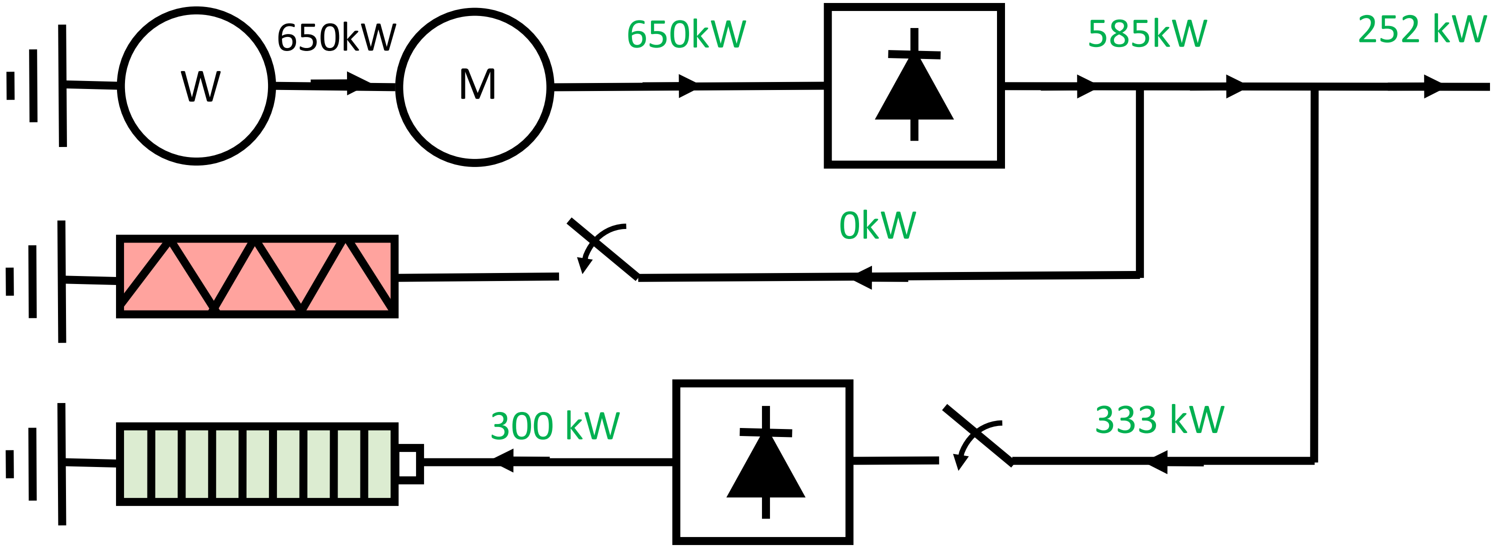
SOC =50% ⟶ P1 = Pmax = 300kW ⟶ Pacc_available = Pmax/Eff= 333kW

Pacc = min (Pacc_available, Ptrain) = min(585,333) = 333kW

Pcat = min(Ptrain-Pacc, Pcat) =min(252, 351) = 252kW
Prhe = Ptrain – Pacc – Pcat = 585 – 333 – 252 = 0kW

Train in braking mode – accumulator charging





SOC1 = 90%
SOC2 = 95%
Pmax = 300kW
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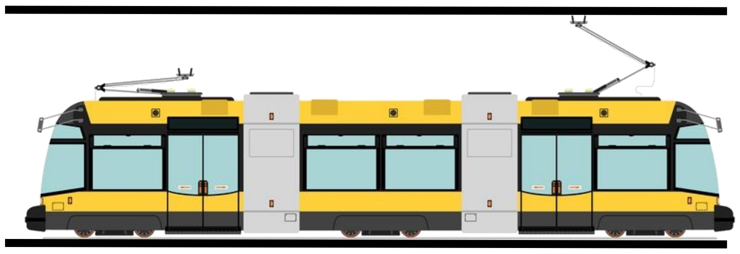
Eff = 90%
Pcat_max = 351kW

Assuming Vcat = 870V and SOC =50%

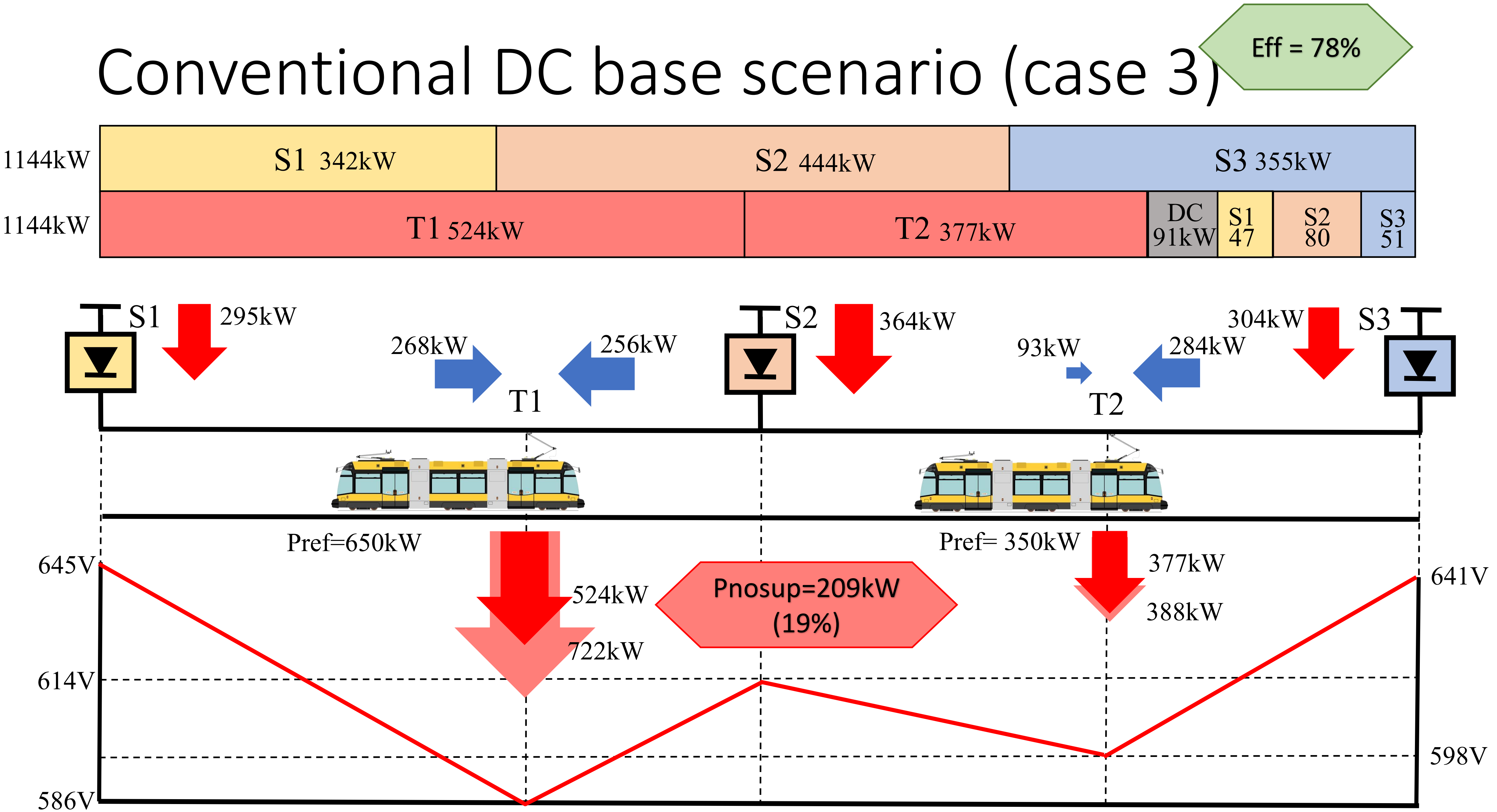


SOC =50% ⟶ P1 = Pmax = 300kW ⟶ Pacc_available = Pmax/Eff= 333kW

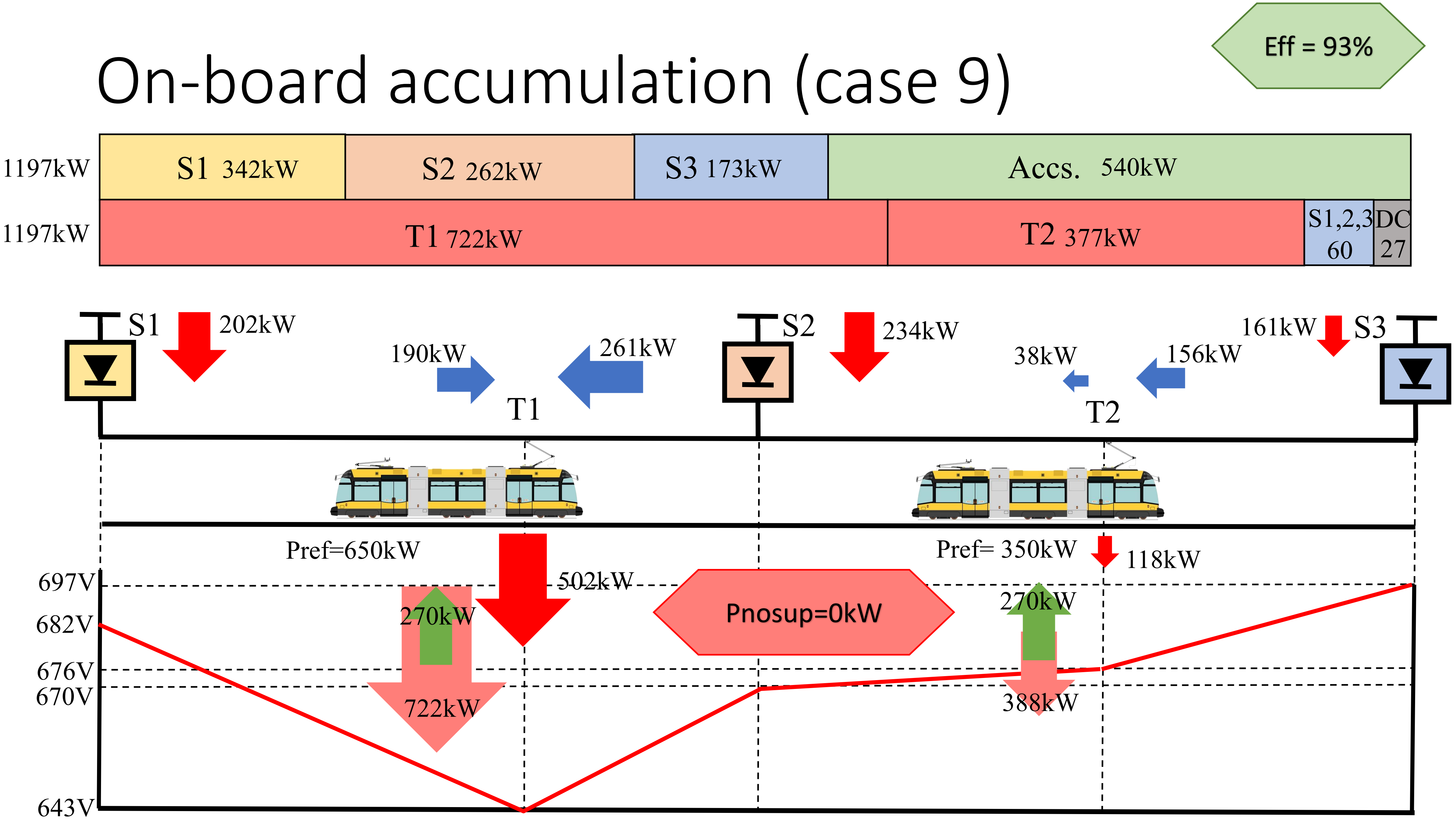
Pacc = min (Pacc_available, Ptrain) = min(585,333) = 333kW

Pcat = min(Ptrain-Pacc, Pcat) =min(252, 351) = 252kW
Prhe = Ptrain – Pacc – Pcat = 585 – 333 – 252 = 0kW

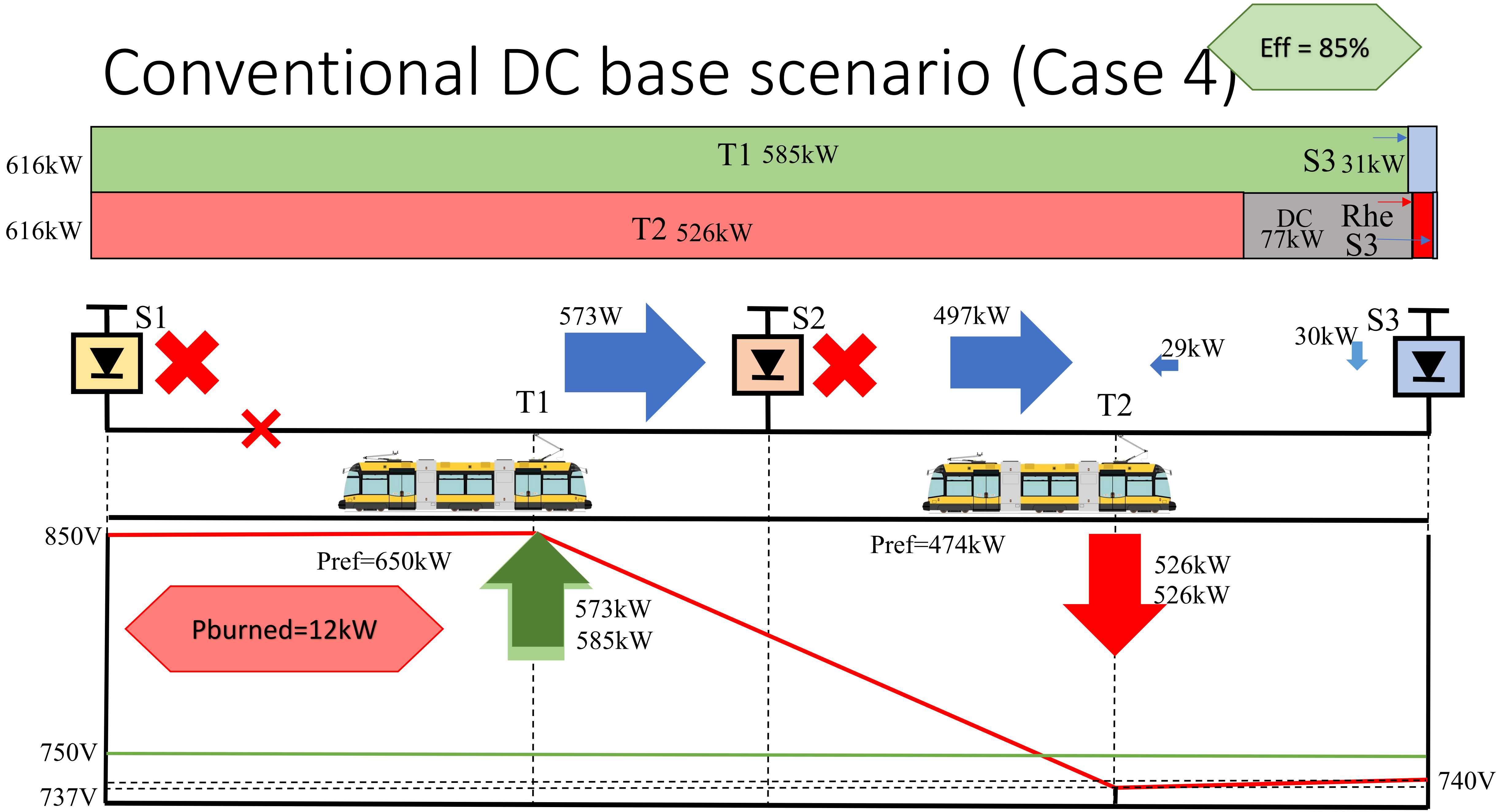
Conventional DC base scenario (case 3)



On-board accumulation (case 9)

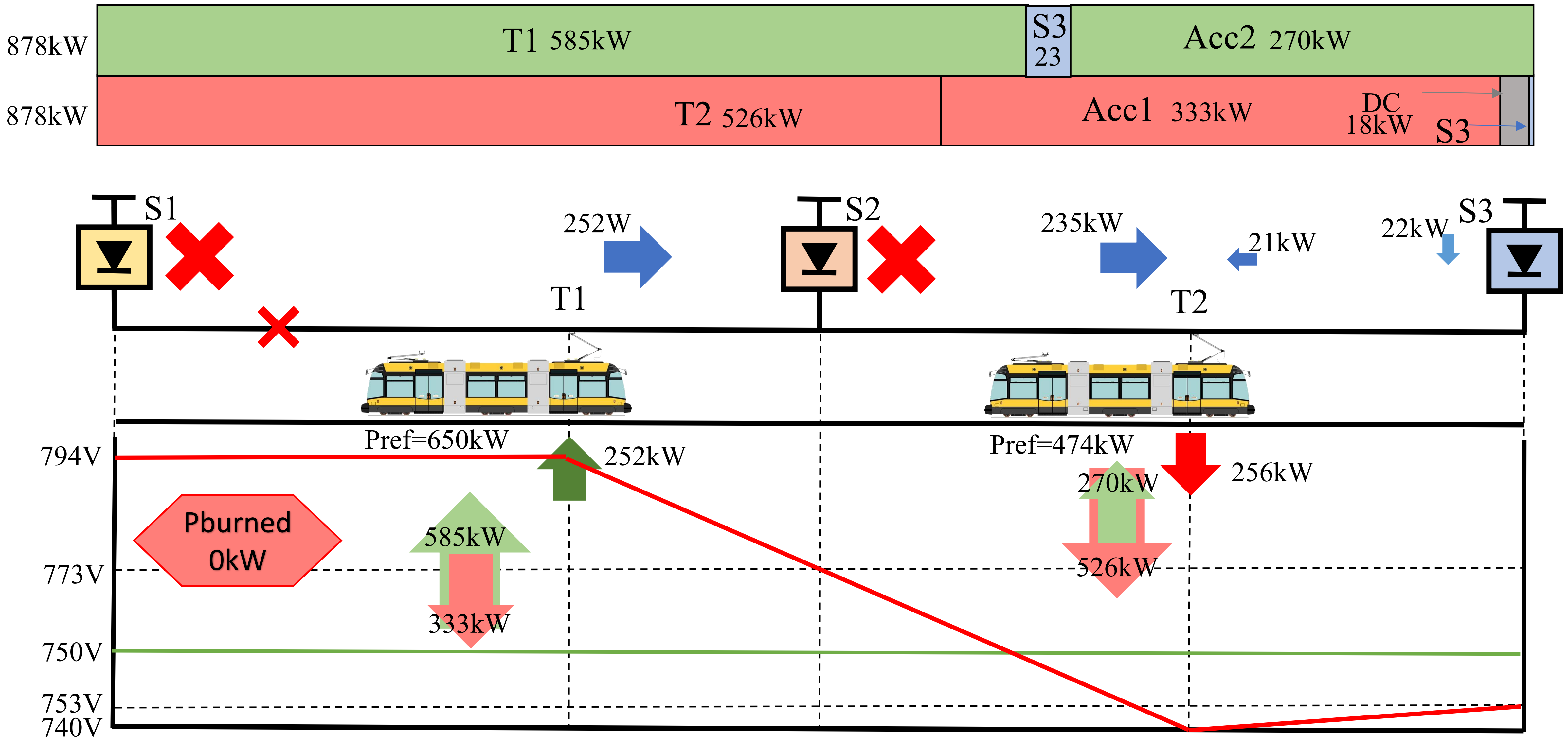


Conventional DC base scenario (Case 4)



On-board accumulation (Case 10)

Eff = 98%



Cases of study (Summary)

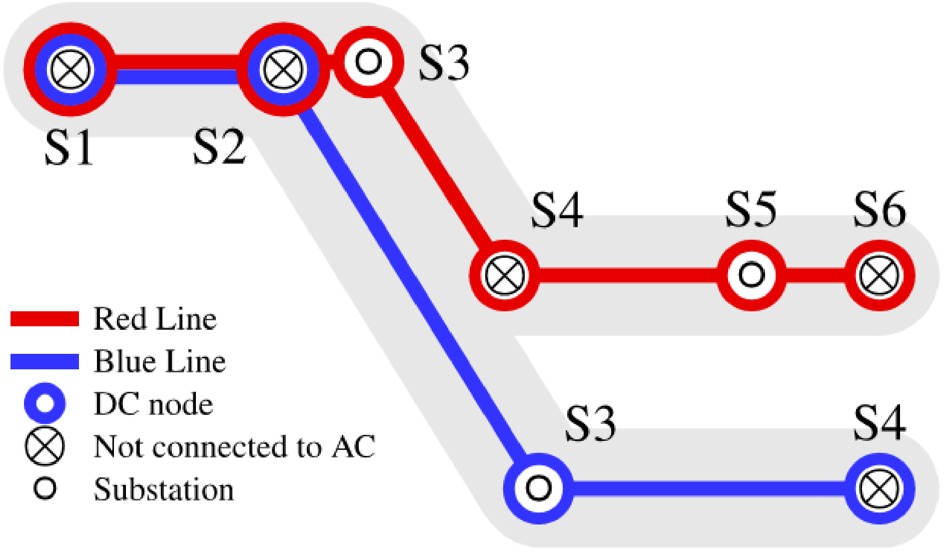
	Substations ****	Trains Acc. ***	Train controls **	Pref T1 *	Pref T2 *	Total P(kW)	P burned (kW)	P non-sup. (kW)	Efficiency (%)
Case 1	Non-reversible	No	No	650	350	1335	0	0	74
Case 2	Non-reversible	No	No	-650	564	658	0	0	85
Case 3	Non-reversible	No	Yes	650	350	1144	0	209	78
Case 4	Non-reversible	No	Yes	-650	474	616	12	0	85
Case 5	Reversible	No	Yes	650	350	1144	0	0	78
Case 6	Reversible	No	Yes	-650	474	693	0	0	90
Case 7	Non-rev + Acc	No	Yes	650	350	1280	0	0	90
Case 8	Non-rev + Acc	No	Yes	-650	474	771	0	0	93
Case 9	Non-reversible	Yes	Yes	650	350	1197	0	0	93
Case 10	Non-reversible	Yes	Yes	-650	474	878	0	0	98

* Negative reference power in the trains means that the train is braking and regenerating
** The considered train controls are the overcurrent protection and the overvoltage protection or squeeze control
*** Trains equipped or not with on-board accumulation system
**** The substations can be conventional (non-reversible), reversible (with dead band) and non-reversible with off-board accumulation

Summary of technologies

Technologies/ Features Bad 🔴 Medium 🟡 Good 🟢		Cost of Infrastructure	Life Cycle Cost	Availability	Safety	Energy Recovery	Catenary Free	Energy Transmission Efficiency	Provider dependency
Reversible Substation		High	Med.	High	High	High	No	High	Low
Energy Storage	Off-Board	High	Med.	High	High	High	No	High	Low
	On-board	Low	Med.	High	High	High	Yes	High	Low

Real Case of Study (3kV DC System)



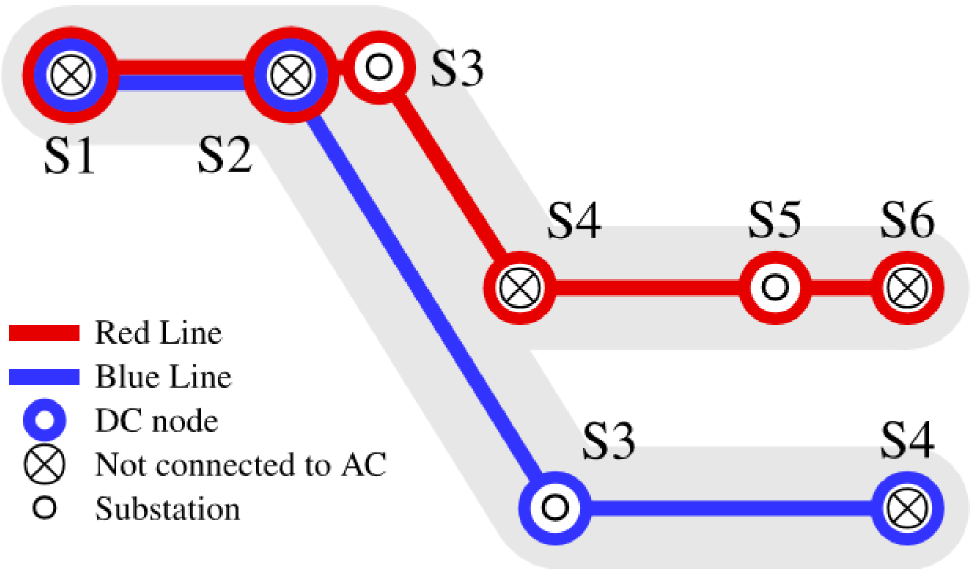
- Red line 30.84km
- Blue line 36.93km
- Substations 3MW
- Short circuit voltage of 5%,
- No load output voltage 3kV
- Voltage at rated load (1000A) is 2880V
- Equivalent impedance in forward mode is 270mΩ
- Equivalent impedance in reverse mode 540mΩ
- Equivalent impedance of the overhead conductor and the rails (return circuit) are respectively 28.605mΩ/km and 7mΩ/km.
- Off board accumulators: 25kWh, 1MW, SOC1,2,3,4 – 0,10,90 and 100%, V1, V2, V3 and V4 will be set respectively to 2685V, 2985V, 3015V and 3315V

Real Case of Study (3kV DC System)

- Rolling Stock
- All EMUs, 5 cars per train
- Total unladen weight of 157.3t.
- Maximum speed 120km/h
- Maximum traction power is 2.2MW
- On-board acc. 7kWh, and 1MW.
- V1, V2, V3 and V4 (1980V,2280V, 3300V and 3600V)

Trip	Required Mechanic. Energy	Mechanic. Regen. Capacity	Required Electrical Energy	Electrical Regen. Capacity	Min. Elect. Consump. Theoretical
S1 to S6 Red	245	112	258	106	151
S6 to S1 Red	240	107	253	102	151
S1 to S4 Blue	243	61	256	58	198
S4 to S1 Blue	187	99	197	94	103
Average Trip	229	95	241	90	151

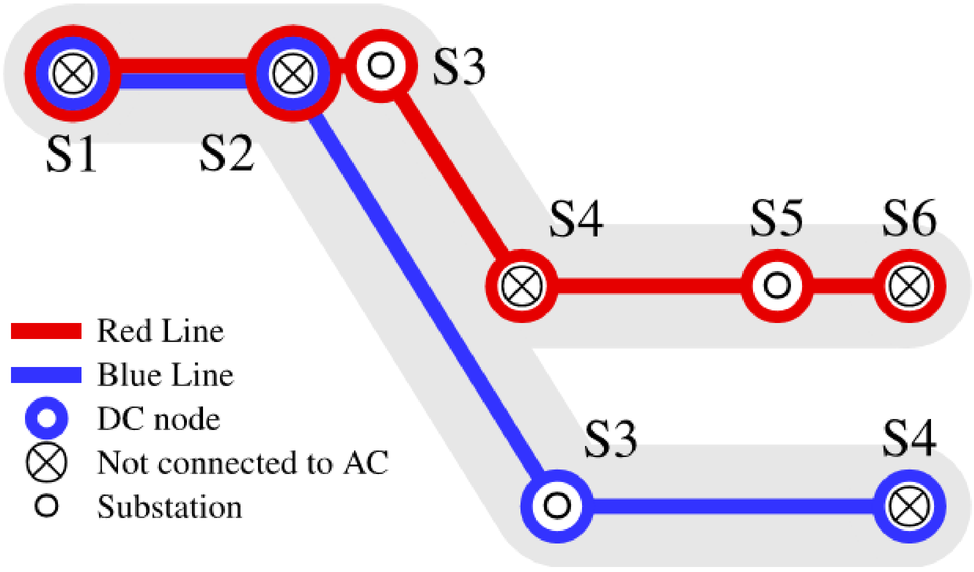
All data in kWh



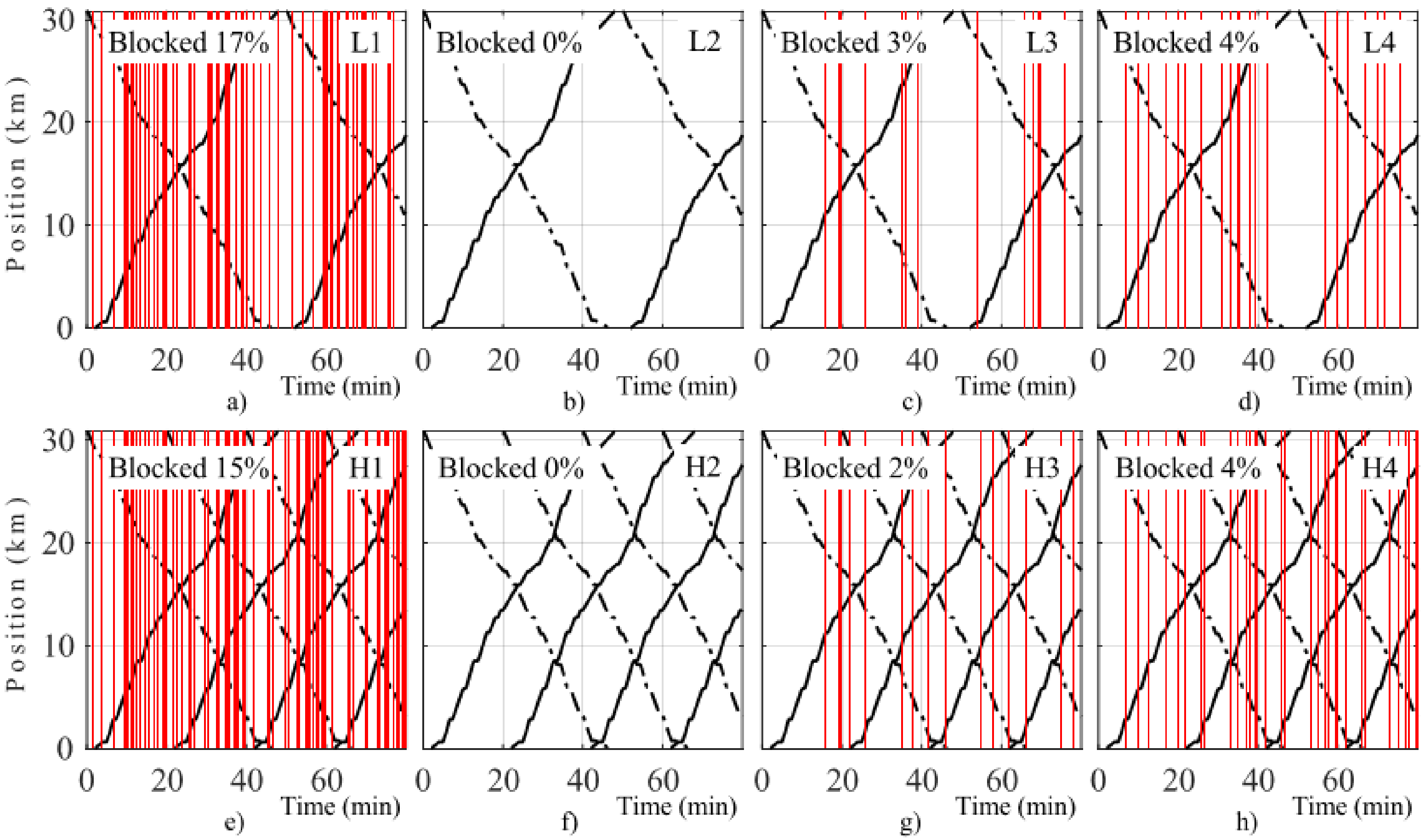
Real Case of Study (3kV DC System)

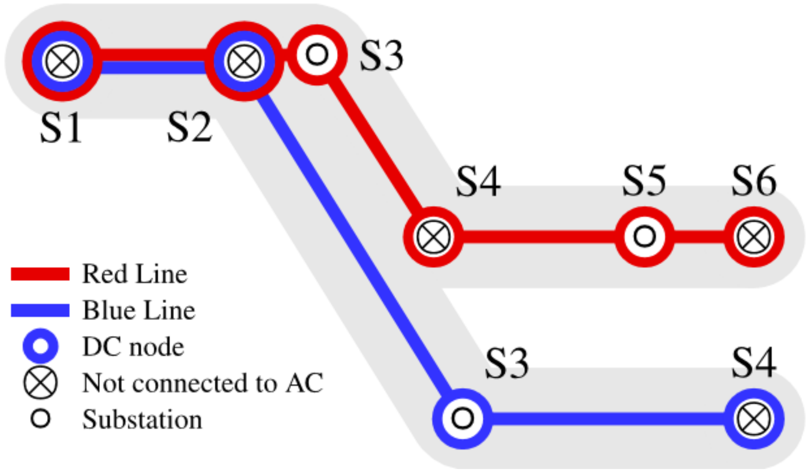
- Simulation interval about 8 hours
- Description of the scenarios:
  - 2 traffic levels

Scenario Code	Traffic Density	Revers. Subst. System	Off-board Acc.	On-board Acc.	Number of Trains	Train Headset (min)
L1	Light	No	No	No	40	50
L2	Light	Yes	No	No	40	50
L3	Light	No	Yes	No	40	50
L4	Light	No	No	Yes	40	50
H1	Heavy	No	No	No	96	20
H2	Heavy	Yes	No	No	96	20
H3	Heavy	No	Yes	No	96	20
H4	Heavy	No	No	Yes	96	20



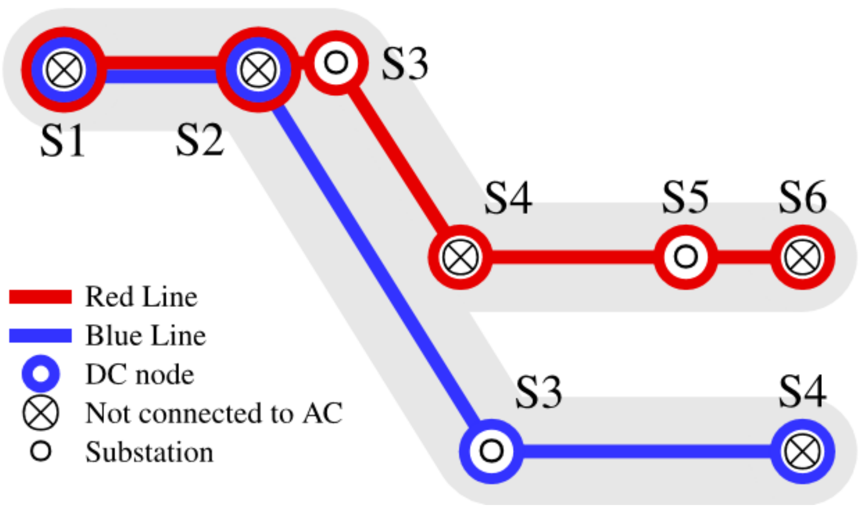
Real Case of Study (3kV DC System)





Real Case of Study (3kV DC System)

	Energy (MWh)							
Scenario	L1	L2	L3	L4	H1	H2	H3	H4
Req. Electrical	9.66	9.66	9.66	9.66	23.08	23.08	23.08	23.08
Reg. Capacity	3.62	3.62	3.62	3.62	8.65	8.65	8.65	8.65
Min. Consumpt.	6.04	6.04	6.04	6.04	14.43	14.43	14.43	14.43
Train. Demand	8.94	9.66	9.59	7.30	21.67	23.08	22.94	17.52
Train Inject.	1.61	3.62	3.26	0.58	5.93	8.65	8.26	2.00
Train Net	7.32	6.04	6.32	6.73	15.74	14.43	14.68	15.52
Rheostatic	2.01	0.00	0.36	0.49	2.72	0.00	0.39	0.79
Non Supp	0.72	0.00	0.07	0.20	1.41	0.00	0.14	0.43
Prov. Subs.	7.64	8.03	6.84	6.93	16.53	17.31	15.62	16.01
Inject. Subs.	0.0	1.69	0.0	0.0	0.0	2.13	0.00	0.0
Sub. Net	7.62	6.34	6.84	6.91	16.52	15.18	15.62	16.01
Grid Losses	0.29	0.30	0.52	0.18	0.78	0.75	0.95	0.48



System Analysis

	Energy in % respec to the electrical energy required by trains							
	L1	L2	L3	L4	H1	H2	H3	H4
Req. Electrical	100	100	100	100	100	100	100	100
Reg. Capacity	37	37	37	37	37	37	37	37
Min. Consumpt.	62	62	62	62	62	62	62	62
Train Demand	92.5	100	99.2	75.5	93.9	100	99.3	75.9
Train Inject.	16.6	37	33.7	5.9	25.7	37.4	35.8	8.6
Train Net	75.8	62.4	65.4	69.6	68.2	62.5	63.5	67.2
Rheostatic	20.8	0	3.7	5.0	11.7	0	1.6	3.4
Non Supp	7.5	0	0.7	2.0	6.0	0	0.6	1.8
Prov. Subs.	79.1	83.0	70.8	71.7	71.6	75.0	67.7	69.3
Inject. Subs.	0	17.4	0	0.1	0	9.2	0	0
Sub. Net	78.8	65.6	70.8	71.5	71.5	65.7	67.6	69.3
Grid Losses	3.0	3.1	5.3	1.9	3.3	3.2	4.1	2.0

Average Train Analysis

	Energy (kWh)							
	L1	L2	L3	L4	H1	H2	H3	H4
Train Demand	224	241	240	183	226	241	239	183
Train Inject.	40	91	82	15	62	90	86	21
Train Net	183	151	158	168	164	150	153	162
Rheostatic	50	0	9	76	28	0	4	69
Non Supp	18	0	2	4	15	0	1	3
Prov. Subs.	191	201	171	173	172	180	163	167
Inject. Subs.	0	42	0	0	0	22	0	0
Sub. Net	191	159	171	173	172	158	163	167
Grid Losses	7	8	13	5	8	8	10	5

Jump to the real simulator

- It is necessary to have a very fast and accurate tool in order to evaluate the effect of the trains and accumulation and other infrastructure devices set-up over the whole system.
- Lets evaluate the Railneos 2.0 simulator developed by the LEMUR research group from the University of Oviedo for CAF Group.

Thanks:

Thanks to CAF company for supporting LEMUR research group research, specially to Urtzi Armendariz and Peru Bidaguren.

Thanks Bassam Mohamed and Islam El-Sayed for their work in the development of the previous described models and the Railneos 2.0 simulator.

Further reading:

P. Arboleya, P. Bidaguren and U. Armendariz, "Energy Is On Board: Energy Storage and Other Alternatives in Modern Light Railways," in *IEEE Electrification Magazine*, vol. 4, no. 3, pp. 30-41, Sept. 2016.

P. Arboleya, "Heterogeneous Multiscale Method for Multirate Railway Traction Systems Analysis," in *IEEE Transactions on Intelligent Transportation Systems* , vol.PP, no.99, pp.1-6

B. Mohamed; P. Arboleya; C. Gonzalez-Moran, "Modified Current Injection Method for Power Flow Analysis in Heavy-Meshed DC Railway Networks with Non-Reversible Substations," in *IEEE Transactions on Vehicular Technology* , vol.PP, no.99, pp.1-1

P. Arboleya, B. Mohamed, C. González-Morán and I. El-Sayed, "BFS Algorithm for Voltage-Constrained Meshed DC Traction Networks With Nonsmooth Voltage-Dependent Loads and Generators," in *IEEE Transactions on Power Systems*, vol. 31, no. 2, pp. 1526-1536, March 2016.