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Contribution to the Energy Efficiency and Environmental Compatibility of Cranes for Inland Waterway/ Feeder Ship Handling

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Basis for the economic efficiency of international supply chains rests on the efficiency of multimodal transport chains. Materials and products are transported along the edges of transport networks with the forwarder endeavouring to maximize the transport efficiency by using the effects of scale along the edges. The network nodes provide the means to have the goods transferred between the means of transport. Whilst purely economic criteria were initially the driving force for a change in the means of transport, ecological requirements are now becoming ever more relevant. The transportation chains should not only be economically presentable but also it makes sense for them to have a "green footprint". In this context the following considerations will deal with the transfer processes within the network nodes, especially those within inland and feeder terminals. Replies are to be given to the questions as to how far the choice of the crane primary drive has an impact on energy consumption and environmental compatibility of handling the goods and which additional benefit does the recuperation of engrained energies bring during the handling process.

[Keywords: port handling, cranes, energy efficiency, CO_2 emissions]

1 STAGE REACHED WITH HARBOUR CRANE DRIVE TECHNOLOGY

1.1 CRANES IN HARBOURS AND INLAND WATERWAY PORTS

Harbour cranes have different functionalities, support structures and energy provision and power transfer components.

In many harbours throughout the world, gantry-type slewing cranes are first choice given that highly specialized terminals for container handling are not involved (cf. /1/, Page 53). The reason lies in their flexible and varied deployment! These cranes permit the handling of bulk goods, classic general cargo and containers. They are on hand for all the usual radii and payloads. The upper structure rotating round the vertical axis of a single or double jib level luffing design is usually arranged in the middle of the gantry which is moved parallel to the ship.

Modern gantry slewing cranes are fitted out with innovative drive and control technology which, in particular, enables excess kinetic and/or potential energy to be recuperated. Ideally the cranes operate on the residential power grid. Despite their operation on rails, one still meets up with cranes fitted out with a diesel-electric or a diesel-hydraulic drive. Here the standard upper structures of mobile harbour cranes have been set 1:1 on portals. However, the advantage of gantry slewing cranes with standard upper structures of mobile harbour cranes tending to be cheaper to acquire is lost in that harbour operators – for ecological reasons – are increasingly putting more and more emphasis on operating their handling equipment on the residential power grid (cf. /2/) – which, in turn, results in a corresponding conversion outlay. (Reference is made to the associated hype surrounding rubber tyred gantry cranes for container handling).

1.2 MAINS FEEDBACK VS. ENERGY STORAGE

The classic gantry crane running on rails – as provided, for instance, by Ardelt – is ideally designed for operation on the residential medium-voltage grid. Hoisting, slewing and luffing gear are electrically operated. Excess kinetic or potential energy can be redistributed under comparatively minor losses via a busbar in the intermediate circuit field between consumers or fed back into the grid if there is no demand.

Compared to the use of local energy accumulators, the advantage behind mains feedback is that the power grid capacity is not limited. The limited capacity of local energy accumulators can become a problem when on lowering hoist loads across a number of cycles more energy is released than is required for the subsequent lifting. This is the case, for instance, when containers are raised from deck positions and deposited on the lower lying quay. The result: the excess energy needs to be dissipated as heat and the recuperation potential drops. Conversely when lowering is undertaken across a number of cycles involving less energy being fed back than required for lifting, a problem can emerge of the diesel engine power not being sufficient – as a result of

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downsizing – to cover the lifting power peaks. This results, for instance, in a reduced hoist speed.

1.3 Energy recuperation technical solutions for diesel-driven cranes

The justification for diesel-operated cranes is either in cases where cranes need to be deployed across surface areas (mobile, floating cranes) or where there is only an unstable power grid or none at all. There are diesel-electric and diesel-hydraulic variants. Both can be optimally fitted out with accumulator systems for energy recuperation purposes.

As early as 1983 a 32-t floating crane having a diesel-electric drive with mechanical flywheel accumulator (under the slewing ring) was placed into operation by MAN in the port of Rotterdam /3/, /4/. Flywheel accumulators, which have been used in busses and trains for many years, have not achieved a breakthrough. They have turned out to be problematical in view of the bearing assembly of the extremely fast turning rotors /5/, /6/.

In their place, Gottwald is today using double-layer capacitors (SuperCaps) for energy storage in diesel-electric run slewing cranes (G HMK). In contrast to conventional batteries, they are distinguished by the required high level of power density /5/. The energy accumulator cannot be used for the recuperation potential from the hydraulically operated luffing movement. Even so, recuperated energy quantities can also be re-distributed here between electrical consumers (see above) to match needs.

For its diesel-hydraulically operated slewing cranes (LHM), Liebherr Nenzing pins its faith on a hydro-pneumatic piston accumulator which on lowering is simultaneously charged with the potential energy of the hoist load when being lowered and the energy supplied from the diesel-hydraulic drive which continues to run. According to Liebherr, the piston accumulator for recuperation potential from slewing and luffing is not made use of. However, the energy being released under conditions of slewing/ luffing would be provided for other consumers via a hydraulic transfer gearbox before being obliterated as heat (see above for analogy to the busbar with electric drives!). This would allow, for instance, the basic load of the crane to be reduced.

It has also been pointed out above that for environmental compatibility reasons some terminal operators set great store on converting diesel operation-designed cranes to electrical operation on the residential power grid. In the case of the hydraulic crane, this means replacing the diesel engine which drives the hydraulic equipment unit by an electric motor. This, in turn, brings about a design drawback. Before it was possible to downsize the diesel engine from the power point of view since it had time during lifting and lowering to undertake its required hoist work. Now a correspondingly larger electric motor needs to be selected in view of the 100% operating time.

With a purely qualitative discussion taking place so far, the idea is now to quantify energy requirements and CO_2 emissions of the duly presented drive variants on the basis of efficiency considerations. To this end a specific final energy need will firstly be formulated in Chapter 2. This is to both establish the general relationship between final energy demand E_E and indicated recuperation potential E_{POT} from position or motion energy. A quantification of the final energy demands E_E of the various drive line configurations will emphasize their differences in terms of energy efficiency and environmental compatibility. Finally in Chapter 3 final energy demands and CO_2 output across the entire service life will be quantified under two case studies and with the aid of the previously established drive train-typical specific final energy demands. Both cases feature a comparison of the various drive train configurations under load lift with focus being put on handling bulk material and on handling containers.

2 System-specific analysis of the various crane drive variants

2.1 Losses in energy recuperation

If cranes are equipped with energy recovery systems, then recuperation efficiencies $\eta_{rek,TW}$ can be formulated for the individual drive unit axes (Formula 1).

$$\eta_{rek,TW} = \eta_{TW} \cdot \eta_{sp\pm} \cdot \eta_{TW} = \eta_{sp\pm} \cdot \eta_{TW}^2 \qquad (1)$$

Efficiency $\eta_{rek,TW}$ takes into account the losses there and back in recuperating potential or kinetic energy via the drive unit (η_{TW}) to the accumulator ($\eta_{sp\pm}$). The drive unit efficiencies considered further on of hoisting gear η_{HW} and slewing gear η_{DW} are each assumed to be equally large in both directions from the amount angle (cf. /6/, S. 4).

Efficiencies η_{HW} (Table 1) depend on the hoisting gear design.

Crane type	Jib type	Reeving	Rope drive - type[1)]	i [2)]	$\eta_{G/Tr}$	η_R	η_{HW}
Slewing crane (G HMK, LHM)	Single jib	None	2/2-2	4	0.941 [3)]	0.985 [3)]	0.886
Slewing crane (Tukan, MAN)	Double jib	None	2/2-2	3			0.900
Cont.crane (Feeder Server)	(Crane trolley)	Simple	4/8-4	3	0.931 [4)]	0.980 [4)]	0.867

[1)] n/z-c with n = No. of rope lines, z = No. of drawn rope ends, c = No. of ropes, [2)] No. of guide pulleys, [3)] Ardelt specification, [4)] KOCKS specification

Table 1. *Establishing hoisting gear efficiency degrees η_{HW}*

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The hoisting gear efficiencies of the harbour slewing cranes being discussed here (no reeving of the cables!) are calculated on the basis of Formula 2.a.

$$\eta_{HW} = \eta_{G/Tr} \cdot \eta_R^i \tag{2a}$$

Hoisting gear efficiency η_{HW} of the slewing cranes takes into account the losses $\eta_{G/Tr}$ of gearbox (here planetary gear), cable-drum and guide pulleys η_R^i with i => No. of pulleys. In considering the various slewing cranes, the efficiencies of comparable hoisting gear components are set to the same level from the amount angle.

For the purposes of comparison, the idea is to continue with a consideration of the recuperation capacity of a container crane of the container feeder type (KOCKS) with rope driven trolley. The simple rope reeving enables calculation here to be undertaken on the basis of Formula 2b.

$$\eta_{HW} = \eta_{G/Tr} \cdot \eta_R^3 \cdot \frac{(1-\eta_R^2)}{2 \cdot (1-\eta_R)} \tag{2b}$$

Regardless of the precise constructional design of the drive unit, an accumulator efficiency $\eta_{sp\pm}$ can still be defined (Formula 3).

$$\eta_{sp\pm} = \eta_{T-S} \cdot \eta_S \cdot \eta_{S-T} = \eta_S \cdot \eta_{T-S}^2 \tag{3}$$

$$\text{with} \quad \eta_{T-S} = \eta_{S-T}$$

Accumulator efficiency $\eta_{sp\pm}$ (Table 2) takes into account the losses between drive unit & accumulator inlet η_{T-S}, the accumulator itself η_S and between accumulator inlet and drive unit η_{S-T}. Losses η_{T-S} on the way to the accumulator are assumed to be just as large from the amount angle as losses η_{S-T} coming away from the accumulator (cf. /4/, Pages 4)! As for the rest, the efficiencies of comparable electrical components are set to the same level from the amount angle – regardless of the crane type involved.

Given allowance for efficiencies η_{HW} and $\eta_{sp\pm}$ determined above, Formula 1 allows recuperation efficiencies $\eta_{rek,HW}$ for the hoisting gears of the various crane configurations to be calculated (Table 3).

"Accumulator type"	Principle	η_{T-S}	η_S	η_{S-T}	$\eta_{sp\pm}$
Mains feedback (Tukan)	Electric	0.87 1)	1.00 -)	0.87 1)	0.76
SuperCaps (G HMK)	Electrostatic - chemical	0.88 2)	0.95 3)	0.88 2)	0.74
Hydraul. pressure reservoir (LHM)	Hydro-pneumatic	0.90 4)	0.96 5)	0.90 4)	0.78
Flywheel accumulator (MAN)	Electro-kinetic	0.88 2)	0.79 6)	0.88 2)	0.62
Mains feedback (Feeder Server)	Electric	0.89 7)	1.00 -)	0.89 7)	0.79
1)Ardelt specification, 2) Own calculations, 3)/5/ 4) Estimate Sauer-Danfoss, 5) Liebherr Nenzing specification, 6)rosseta Technik specification , 7)KOCKS specification					

Table 2. *Establishing accumulator efficiencies $\eta_{sp\pm}$*

Crane type	Accumulator type	Jib type	$\eta_{sp\pm}$	η_{HW}	$\eta_{rek,HW}$
Tukan	Mains recovery	Double jib	0.76	0.900	0.61
G HMK	SuperCaps	Single jib level luffing	0.74	0.886	0.58
LHM	Hydraul. pressure reservoir	Single jib level luffing	0.78	0.886	0.61
MAN	Flywheel accumulator	Double jib	0.62	0.900	0.50
Feeder Server	Mains recovery	(Crane trolley)	0.79	0.867	0.59
N.N.	Without energy recovery	N.N.	0.0	N.N.	0.0

Table 3. *Establishing recuperation efficiencies $\eta_{rek,HW}$ for the hoisting gears*

Slewing crane type	Accumulator type	$\eta_{sp\pm}$	η_{DW}	$\eta_{rek,DW}$
Tukan	Mains recovery	0.76	0.90 1)	0.61
G HMK	SuperCaps	0.74		0.60
MAN	Flywheel accumulator	0.62		0.50
N.N.	Without energy recovery	0.0	N.N.	0.0
1) Verschoof, J.: Cranes – Design, Practice and Maintenance (1999)				

Table 4. *Establishing recuperation efficiencies $\eta_{rek,DW}$ for the slewing gears*

Recuperation efficiencies $\eta_{rek,DW}$ for the slewing gears being discussed (electrically driven) (Table 4) are calculated accordingly.

The established recuperation efficiencies $\eta_{rek,HW}$ and $\eta_{rek,DW}$ for cranes with energy recovery would suggest that as far as the drive/ accumulator systems are concerned – normally used today in harbour slewing cranes (i.e. with no allowance given for the diesel-electric variant with flywheel accumulator) – some 40 % of the potential and/or kinetic energy being released during recuperation is dissipated as heat. (This also applies to the hoist axis of the Feeder Server.)

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That is why the assumption is one of a recuperation efficiency (under favourable operating circumstances, see above!) of

$\eta_{rek} = \eta_{rek,HW} = \eta_{rek,DW} = 0.60$

when consideration is given below to the cranes with energy recovery. The approx. 40% losses in recuperation are to be offset by the use of final energy sources (diesel or power from the grid).

Note: In view of the "shorter paths", the recuperation efficiencies – which are not gone into any further here – in redistributing energy between consumers via busbars or hydraulic transfer gearbox (see above) tend to be larger from the amount angle than the above 60 %!

2.2 Losses in transforming final energy into effective energy

The heat losses in transforming final energy (E) into effective energy (N) – i.e. between the diesel engine tank or alternatively public power grid terminals and drive unit inlet (motor shaft) – are to be taken into account with efficiencies $\eta_{E\text{-}N}$ (Table 5).

2.3 Specific final energy need with recuperation

The specific final energy need e_E in kWh per 1 kWh of kinetic or potential energy at the effective location of the drive unit axles is calculated on the basis of Formula 4.

$$e_E = \frac{1-\eta_{rek}}{\eta_{E-N} \cdot \eta_{TW}} \tag{4}$$

As regards resources consumption (primary energy requirement) of the crane with energy recuperation, that fact that the specific final energy need in kWh/kWh – when operating the crane on the electricity grid – is only just under half of that when operating the crane per diesel engine needs to be put into perspective. The reason: under the circumstances prevailing today (German power plant mix, centralized energy generation), efficiency $\eta_{P\text{-}E,el} = 0.32$ involved in the generation and conveyance of electricity is clearly worse than $\eta_{P\text{-}E,foss} = 0.87$ which is involved in refining and transporting natural oil derivatives.

Drive type	Definite loss-incurring drive components	$\eta_{E\text{-}N}$ [1)] Electr.	$\eta_{E\text{-}N}$ [1)] Diesel
electric-electric	Cables, cable reels, transformer, inverter, electrical motor	0.87-0.89	
electro-hydrostat.	Cables, cable reel, transformer, e-motor, hydr. pump, tubing, (accumulator), hydr. motor	0.73	
diesel-electric	Diesel engine, generator, inverter, electric motor		0.36
diesel-hydrostatic	Diesel engine, hydr. pump, tubing, (accumulator)), hydr.motor		0.34
[1)] Own calculation			

Table 5. *$\eta_{E\text{-}N}$ efficiencies of various drive chains in transforming final energy into effective energy*

Crane type	Drive type	$\eta_{E\text{-}N}$	Accumulator type	η_{rek}	η_{TW} Single jib level luffing	η_{TW} Double-jib level luffing	η_{TW} Slewing gear	e_E [kWh/kWh] Electr.	e_E [kWh/kWh] Diesel	Crane type
Lifting										
Tukan	Electric-electric	0.87	Grid	0.60		0.900		0.51		Tukan
G HMK	Diesel-electric	0.36	SuperCaps	0.60	0.886				1.25	G HMK
G HMK (grid)	Electric-electric	0.87						0.52		G HMK (grid)
LHM	Diesel-hydrostatic	0.34	Hydro-pneumatic	0.60	0.886				1.33	LHM
LHM (grid)	Electro-hydrostatic	0.73						0.61		LHM (grid)
Feeder Server	Electric-electric	0.89	Grid	0.60	Trolley: 0.867			0.52		Feeder Server
Slewing										
Tukan/ G HMK	Electric-electric	0.87	Grid	0.60			0.90	0.51		Tukan/ G HMK
G HMK	Diesel-electric	0.36	SuperCaps	0.60			0.90		1.23	G HMK
for comparison: Cranes without energy recuperation system										
G HMK	Diesel-electric	0.36	Without accumulator	0.0	0.886				3.13	G HMK
LHM	Diesel-electr./ hydraul.	0.34	Without accumulator	0.0	0.886				3.32	LHM
G HMK	Diesel-electric	0.36	Without accumulator	0.0			0.90		3.09	G HMK

Table 6. *Establishing the specific e_E energy needs on lifting & slewing acceleration*

With the aid of specific final energy need e_E (Table 6), the absolute final energy needs E_E can be ascertained for given recuperation potentials E_{POT} from position or motion energy (Formula 5).

$$E_E = e_E \cdot E_{POT} \tag{5}$$

Energy need and CO_2 emissions are proportional to each other. As such with the aid of the cumulative

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specific CO_2 emissions $m_{CO2,spez}$ (Table 7), the absolute CO_2 emissions m_{CO2} can be calculated from the E_E final energy need (Formula 6).

$$m_{CO2} = E_E \cdot m_{CO2,spez} \qquad (6)$$

	Power plant current [1)]	Fossil (Diesel) [2)]
EU	0.45 t/MWh	
Germany (D)	0.58 t/MWh	
China/ Russia	1.00 t/MWh	
Global		0.32 t/MWh
[1)] /7/, [2)] cf. /8/		

Table 7. *Cumulative specific CO_2 emissions $m_{CO2,spez}$ of power plant current & diesel fuel (final energy consideration)*

3 Case Studies

3.1 Case Study 1: Quantification of energy needs and CO_2 emissions as a result of Hoist work with bulk material handling of 2 million duty cycles (U7)

3.1.1 Content

With n = 2 million duty cycles/ life cycle (U7 handling class as per DIN EN 14985), h=10.5 m mean lifting height and a mean hoist load of m_{brt} = 14.8 t given a gripper weight of m_{tara} = 5.8 t, $W_{Hub,U7}$ hoist work to be performed and recuperation potential from position energy $E_{POT} = E_{pot,U7}$ result in:

$$W_{Hub,U7} = 2 \cdot 10^6 \cdot 14{,}8 \cdot 9{,}81 \cdot 10{,}5\ kNm = 847\ MWh$$

$$E_{pot,U7} = 2 \cdot 10^6 \cdot 5{,}8 \cdot 9{,}81 \cdot 10{,}5\ kNm = 332\ MWh$$

In calculating the final energy need of electricity or diesel fuel $E_{E,Hub,U7}$ (Table 8), it is assumed that the bulk material is ejected at the end of the lifting path i.e. only the intrinsic weight of the gripper is available for energy recuperation in the lowering (Formula 7):

$$E_{E,Hub} = \frac{W_{Hub} - E_{POT}}{\eta_{E-N} \cdot \eta_{HW}} + e_E \cdot E_{POT} = \frac{W_{Hub} - \eta_{rek} \cdot E_{POT}}{\eta_{E-N} \cdot \eta_{HW}} \qquad (7)$$

Final energy:

$$E_{E,Hub,U7} = \frac{(847 - 0{,}6 \cdot 332)MWh}{\eta_{E-N} \cdot \eta_{HW}} = \frac{648\,MWh}{\eta_{E-N} \cdot \eta_{HW}}$$

with: $(\eta_{rek} \cdot E_{POT}) / W_{Hub}$ = 24 %

at: 2,000,000 · 14.8 t = 29.6 Mt cumulative net load

Crane type	Drive type	Accumulator type	η_{E-N}	η_{HW}	$E_{E,Hub,U7}$ [MWh]		$E_{E,Hub}/t$	CO_2 [t]		ΔCO_2
					Electr. grid	Diesel	[kWh/t]	Electr. (D)	Diesel	
Tukan	Electric-electr.	Grid	0.87	0.900	830		0.028	480		± 0 %
G HMK	Diesel-electric	SuperCaps	0.36	0.886		2,030	0.069		650	+ 35 %
G HMK (grid)	Electric-electr.		0.87		840		0.028	490		+ 2 %
LHM	Diesel-hydrostat.	Hydropneumatic	0.34	0.886		2,150	0.073		690	+ 44 %
LHM (grid)	Elect.-hydrostat.		0.73		1,000		0.034	580		+21 %
For comparison: Cranes without energy recuperation system (no accumulator, no redistribution)										
G HMK	Diesel-electric	Without	0.36	0.886		2,660	0.090		850	+ 77 %
LHM	Diesel-hydrostat.	Without	0.34	0.886		2,810	0.095		900	+ 87 %

Table 8. *Final energy need & CO_2 emission of various drive concepts of slewing cranes when undertaking load lift (Bulk goods handling in inland waterway ports, life cycle consideration)*

3.1.2 Discussion of the findings

The quantitative benefits in relation to energy efficiency and pollutant emissions of cranes with the scope for energy recuperation as against those without are quite striking. As such, the benefits of a mains feedback as against local energy accumulators will be gone into below.

The specific energy consumption of all-electric cranes of 0.028 kWh per handled ton of gripper goods is the most favourable one regardless of whether excess energy is fed back into the grid or stored locally.

Consumption and CO_2 emission of the electro-hydrostatic variant is some 20% above that of the all-electric cranes.

The disadvantage of diesel-operated cranes as against those supplied with electricity from the grid in matters of pollutant emissions is striking. Under the practical relevant operating program as the basis of the comparison, harbour cranes generate 35% and 45% more CO_2 under diesel-electric and diesel-hydraulic operation respectively than the operation of all-electric cranes.

3.2 Case Study 2: Quantification of energy needs and CO_2 emissions as a result of Hoist work with container handling of 4 million duty cycles (U8)

3.2.1 Content

The loading and unloading of container ships is based on Handling Class U8 (as per DIN EN 14985), which is equivalent to n = 4 million duty cycles/ life cycle.

A mean weight per TEU of 14 t and a 60 % share of 40‘ containers produce a mean weight per box of 22.4 t.

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Only a single lift operation is considered. The tare weight of spreader plus rotator (with the slewing crane) or plus head block (with the container crane) adds up to 9 t plus 2.6 t = 11.6 t.

The assumption further is that feeder ships (here: Sietas Type 168) are fully unloaded and loaded in the hub terminal. This ensures that representative spaces for containers on and under deck can be established. Handling frequencies (37.5 % on-deck containers, 62.5 % under-deck containers) and average paths in loading and unloading (see Fig 1) can be assigned to the representative spaces.

With allowance made for the handling frequency, mean hoist paths and mean weight per box, $W_{Hub,U8}$ = 4,100 MWh of hoist work is to be undertaken at the crane "hook" during the service life. In the event of mains feedback, the total potential energy $E_{pot,U8} = W_{Hub,U8}$ = 4,100 MWh can be used for recuperation. Due to the above-addressed asymmetry between hoist work and recuperation potential – resulting, in turn, from the elevation

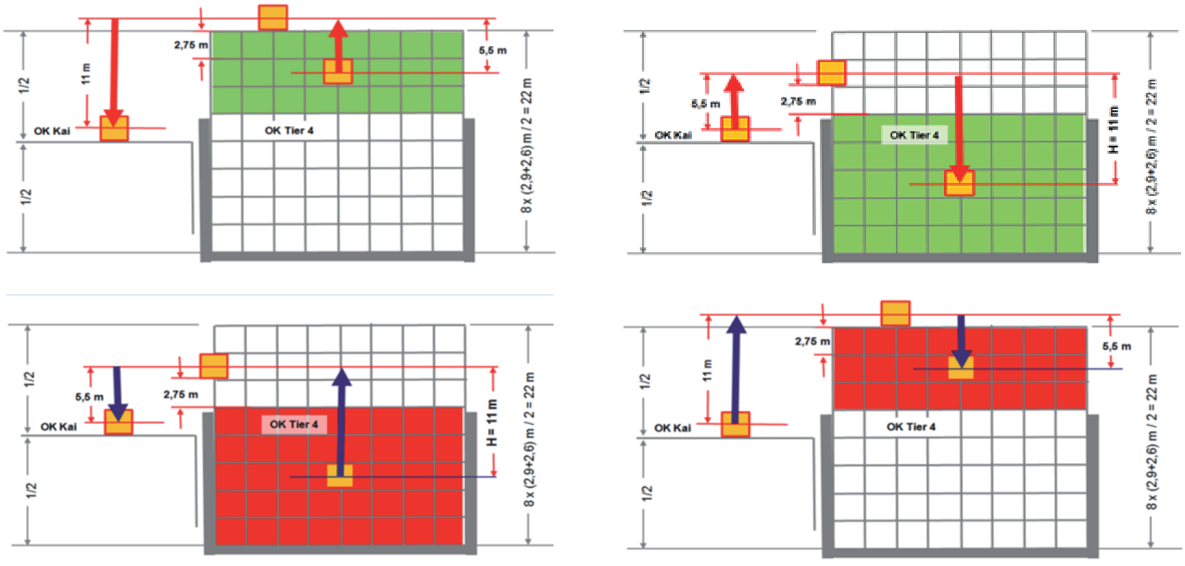

Figure 1. Representative hoist paths when fully loading/unloading Sietas 168-type feeder ships

difference between source and sink under a specified working sequence – cranes with a local energy accumulator, in contrast, only have 0.84 x $E_{pot,U8}$ = 3,430 MWh as recuperation potential E_{POT}

The assumption behind this case study is the involvement of a terminal specialized in container handling. As a comparison, an all-electric feeder server-type container crane specially tailored to feeder handling (see above!) replaces the corresponding slewing crane.

The final energy need for electricity or diesel fuel $E_{E,Hub,U8}$ (Table 9) is calculated in a similar way to the considerations associated with bulk goods handling using Formula 7

Final energy need given mains feedback:

$$E_{E1,Hub,U8} = \frac{(4.100 - 0{,}6 \cdot 4.100)MWh}{\eta_{E-N} \cdot \eta_{HW}} = \frac{1.640MWh}{\eta_{E-N} \cdot \eta_{HW}}$$

with: $(\eta_{rek} \cdot E_{POT1}) / W_{Hub} = 60\ \% = \text{Max}$

Final energy need with local energy storage:

$$E_{E2,Hub,U8} = \frac{(4.100 - 0{,}6 \cdot 3.430)MWh}{\eta_{E-N} \cdot \eta_{HW}} = \frac{2.040MWh}{\eta_{E-N} \cdot \eta_{HW}}$$

with: $(\eta_{rek} \cdot E_{POT2}) / W_{Hub} = 50\ \%$

in each instance given: 4,000,000 · 22.4 t = 89.6 Mt cumulative net load

3.2.2 DISCUSSION OF THE FINDINGS

Even initially more striking than with bulk goods handling are the quantitative benefits of energy recuperation associated with container handling. The justification for them comes from the greater recuperation potential of 50 % or 60 % with container handling as against 24 % with bulk goods handling.

From now on it is a matter of discussing the benefits of mains feedback as against local energy accumulators.

In view of the fact that certain conditions produce a situation whereby a local accumulator is no longer able to adequately take up or deliver energy (see above!), the all-

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electric crane with mains feedback – something which affects low consumption and environmental compatibility – takes up the pole position!

However, the share of recuperable energy is more likely in practice to be above 85 % since given a feedback of several consumers in a specified instance the storage of energy will take second place to its redistribution (see above!).

To the extent that the calculation of specific energy needs and CO_2 emissions is based on the "other extreme" in that cranes with local energy accumulator are provided with the entire recuperation potential of 4,100 MWh (Table 10), then the picture arising is a similar one to that associated with the handling of bulk goods (Tab. 8).

Crane type	Drive type	Accumulator type	η_{E-N}	η_{TW}	$E_{E,Hub,U8}$ [MWh]		$E_{E,Hub}$/t [kWh/t]	CO_2 [t]		Δ CO_2
					Electr. grid	Diesel		Electr. (D)	Diesel	
Feeder Server	Electric-electr.	Grid	0.89	0.867	2,130		0.024	1,240		± 0 %
G HMK	Diesel-electric	SuperCaps	0.36	0.886		6,400	0.071		2,050	+ 65 %
G HMK (grid)	Electric-electr.		0.87		2,650		0.030	1,540		+ 24 %
LHM	Diesel-hydrostat.	Hydro-pneumatic	0.34	0.886		7,140	0.080		2,280	+ 84 %
LHM (grid)	Elect.-hydrostat.		0.73		3,150		0.035	1,830		+ 48 %
For comparison: Cranes without energy recuperation system (no accumulator, no redistribution!)										
G HMK	Diesel-electric	Without	0.36	0.886		12,850	0.152		4,110	+ 230 %
LHM	Diesel-hydrostat.	Without	0.34	0.886		13,610	0.152		4,360	+ 250 %

Table 9. *Final energy need and CO2 emissions of various drive concepts of harbour cranes under conditions of load lift (container handling in feeder harbours, Life Cycle consideration) at E POT,U8 = 0.84 x Epot,U8 in the case of local accumulators*

Crane type	Drive type	Accumulator type	η_{E-N}	η_{TW}	$E_{E,Hub,U8}$ [MWh]		$E_{E,Hub}$/t [kWh/t]	CO_2 [t]		Δ CO_2
					Electr. grid	Diesel		Electr. (D)	Diesel	
Feeder Server	Electric-electr.	Grid	0.89	0.867	2,130		0.024	1,240		± 0 %
G HMK	Diesel-electric	SuperCaps	0.36	0.886		5,140	0.057		1,640	+ 32 %
G HMK (grid)	Electric-electr.		0.87		2,130		0.024	1,240		± 0 %
LHM	Diesel-hydrostat.	Hydropneu-matic	0.34	0.886		5,440	0.061		1,740	+ 40 %
LHM (grid)	Elect.-hydrostat.		0.73		2,540		0.028	1,470		+ 19 %
For comparison: Cranes without energy recuperation system (no accumulator, no redistribution!)										
G HMK	Diesel-electric	Without	0.36	0.886		12,850	0.152		4,110	+ 230 %
LHM	Diesel-hydrostat.	Without	0.34	0.886		13,610	0.152		4,360	+ 250 %

Table 10. *Final energy need & CO_2 emissions of various drive concepts of harbour cranes under load hoist conditions (container handling in feeder harbours, life cycle consideration) with $E_{POT,U8} = 1 \times E_{pot,U8}$ in the case of local accumulators*

4 Summary

Harbour slewing cranes of a gantry design are considered to be primarily in line for quay-linked inland waterway ship and/or feeder handling. They are multi-purpose-enabled. Container cranes lend themselves especially for box handling operations.

Cranes running on rails are usually supplied with energy from the fixed power grid. Complete standard upper structures of mobile cranes being fitted onto gantries use the pre-configurated diesel-electric/hydrostatic drive or can also be run on the power grid following conversion.

The scope is on hand for all drive variants to recover either potential or kinetic energy by either distributing excess energy directly onto other consumers or buffering energy in the meantime for later use if there is no immediate demand.

As an alternative to a feedback into the electricity grid, examinations have been conducted on flywheel accumulators, SuperCaps and hydro-pneumatic piston accumulators to be installed on the crane side as a function of drive. The flywheel accumulator was more or less discarded straight away in view of a comparatively low accumulator efficiency.

The examinations also point to the fact that mains feedback and crane-sided accumulator systems based on SuperCaps or hydro-pneumatic piston accumulators operate in a similarly efficient manner – i.e. that up to 60 % of the recuperation potential from kinetic or potential energy being released can be recuperated at the same effective location. There is a tendency for minor losses to arise when other consumers directly use energy which has been released.

As part of two case studies – one for bulk goods handling in inland waterway ports and one for container handling at the feeder mooring – the life-long energy consumptions and CO_2 emissions resulting from hoist work have been established for various energy accumulator concepts. All-electric cranes with mains feedback are clearly superior in terms of consumption and

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CO_2 emissions to all the others and especially those with diesel drive. Even if assumed – on the beneficial side – in container handling that the capacities of the crane-sided installed energy accumulators do not significantly limit the recuperation potential when lowering is undertaken, it can still be demonstrated, for instance, that the electro-hydrostatically-operated crane, the diesel-electrically-operated crane and the diesel-hydrostatically operated crane emit 20%, 30 – 35 % and 40 – 45 % more CO_2 respectively than cranes operating from the power grid. On the other hand diesel-operated cranes without any scope for energy recuperation emit up to 3.5 times more CO_2 than the crane operating with mains feedback on the power grid. The specific consumptions per hoist at the inland waterway/feeder ship mooring – given the same recuperation potential – vary between 0.024 and 0.034 kWh/t for cranes on the fixed electricity grid and between 0.057 and 0.073 kWh/t for diesel-operated cranes with local energy accumulators. Diesel-operated cranes without any energy recuperation possibility have up to a 6-fold final energy need in kWh.

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